

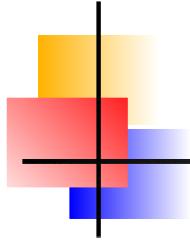
Theoretical Implications of $0\nu\beta\beta$ Decay Measurements

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<http://www.astroparticles.es/>



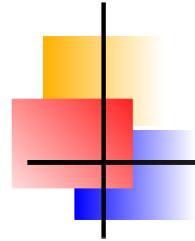
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II. General $0\nu\beta\beta$ decay operator decomposition

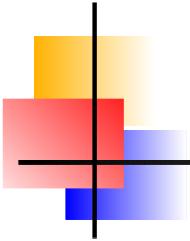
III. Lepton Number Violation, $0\nu\beta\beta$ and LHC

IV. Conclusions



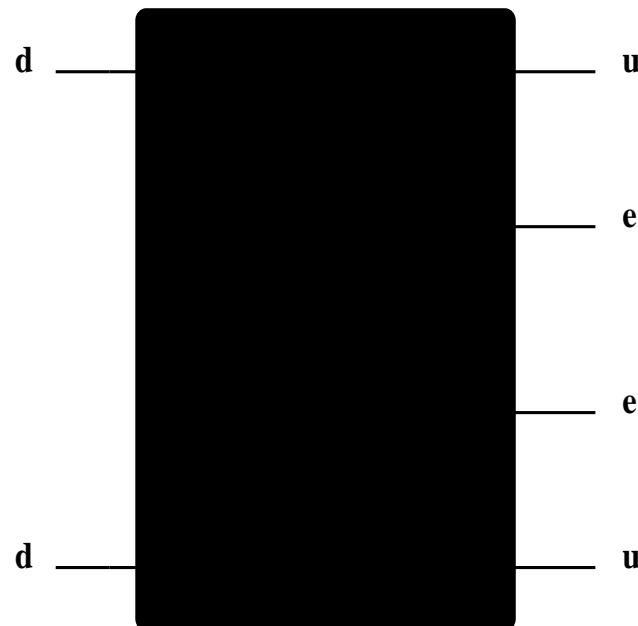
$\mathcal{I}.$

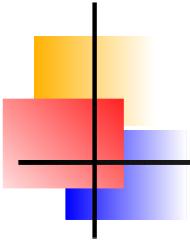
Introduction



Black Box: Experiment

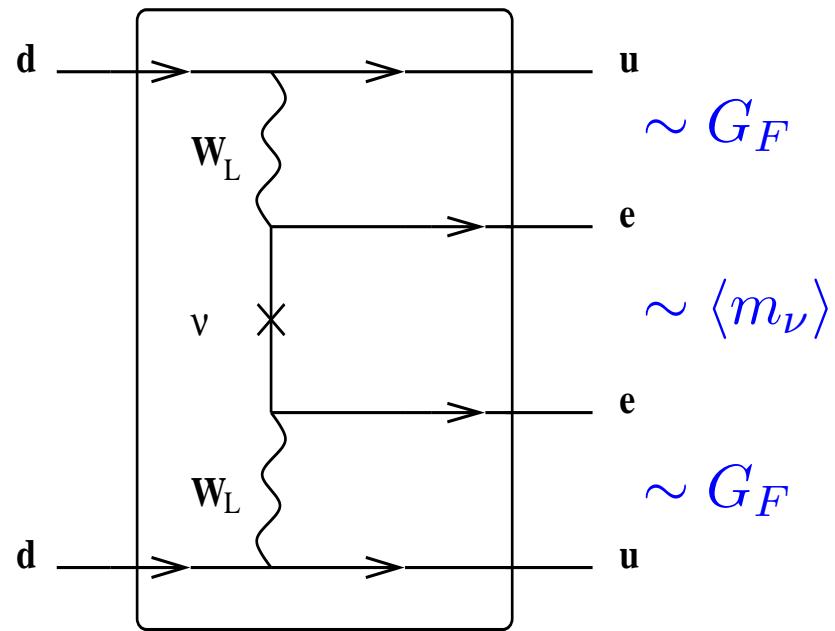
The experimentalist sees:





Mass mechanism

The experimentalist sees:



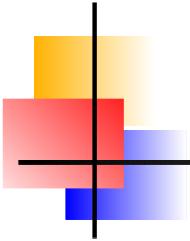
$$\sim G_F$$

$$\sim \langle m_\nu \rangle$$

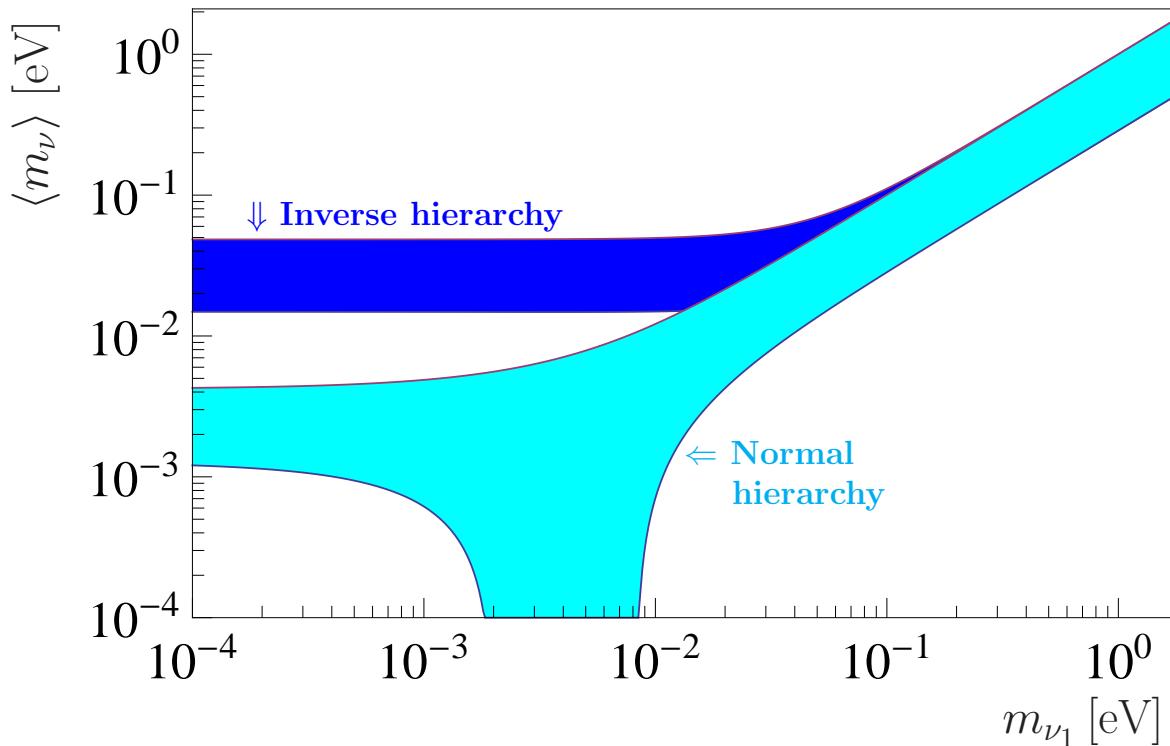
$$\sim G_F$$

With $T_{1/2}^{0\nu\beta\beta}(^{136}Xe) \geq 1.6 \times 10^{25}$ yrs:

$$\sim \langle m_\nu \rangle \lesssim (0.2 - 0.4) \text{ eV}$$



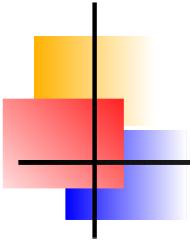
$\langle m_\nu \rangle$ versus m_{ν_1} : May 2014



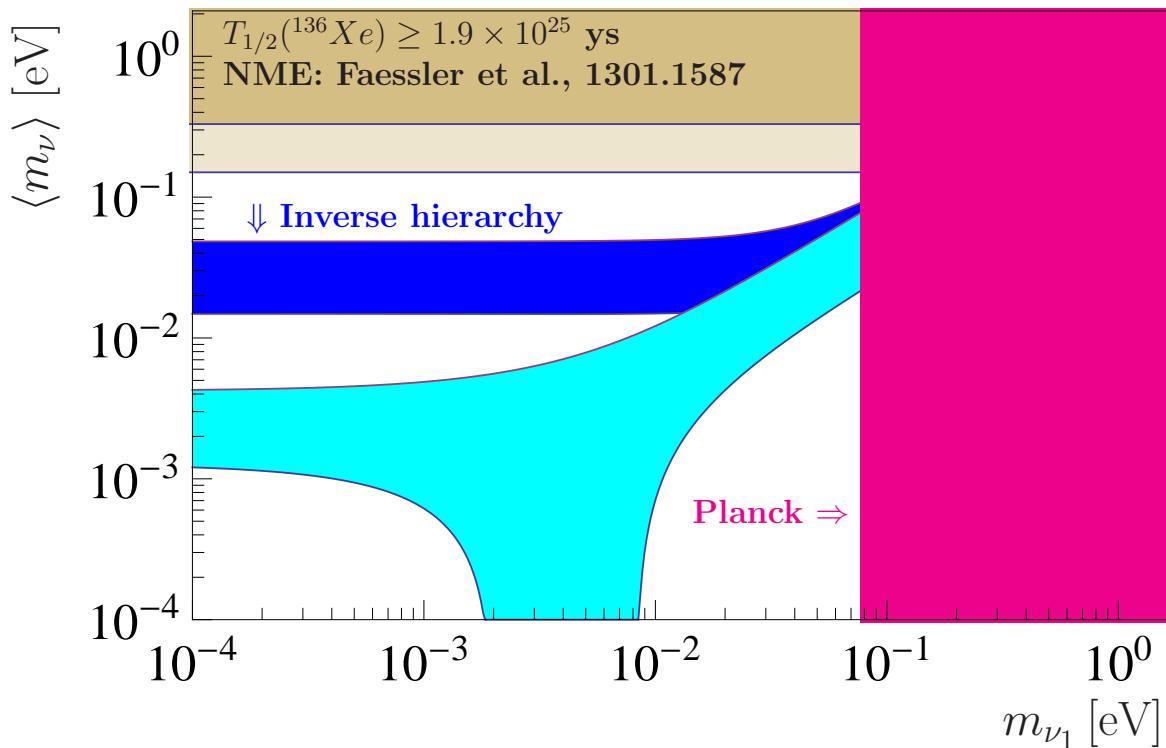
Global fit data from:

Forero, Tortola
& Valle, arXiv:1405.7540

all ranges at 1σ c.l.



$\langle m_\nu \rangle$ versus m_{ν_1} : May 2014



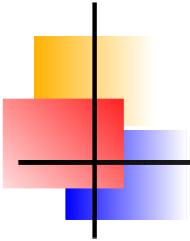
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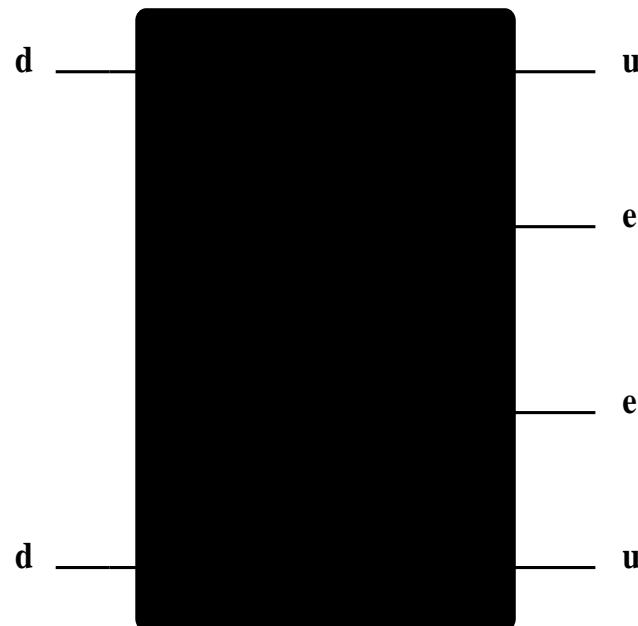
For mass hierarchy
see talk by W. Winter

For CP violation
see talk by S. Pascoli



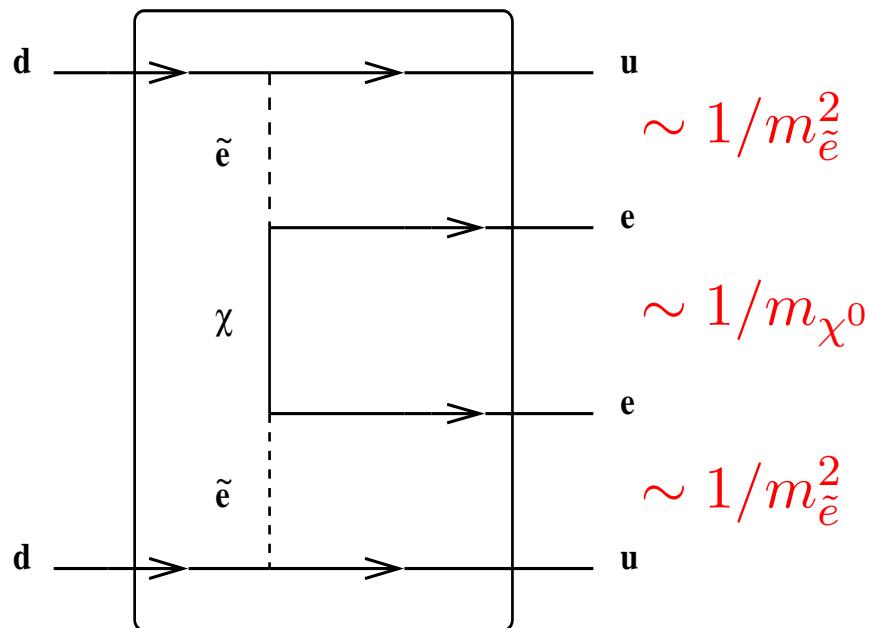
Black Box: Experiment

The experimentalist sees:



R_P violating SUSY

The experimentalist sees:



$$\sim 1/m_{\tilde{e}}^2$$

$$\sim 1/m_{\chi^0}^2$$

$$\sim 1/m_{\tilde{e}}^2$$

Only one example
diagram!

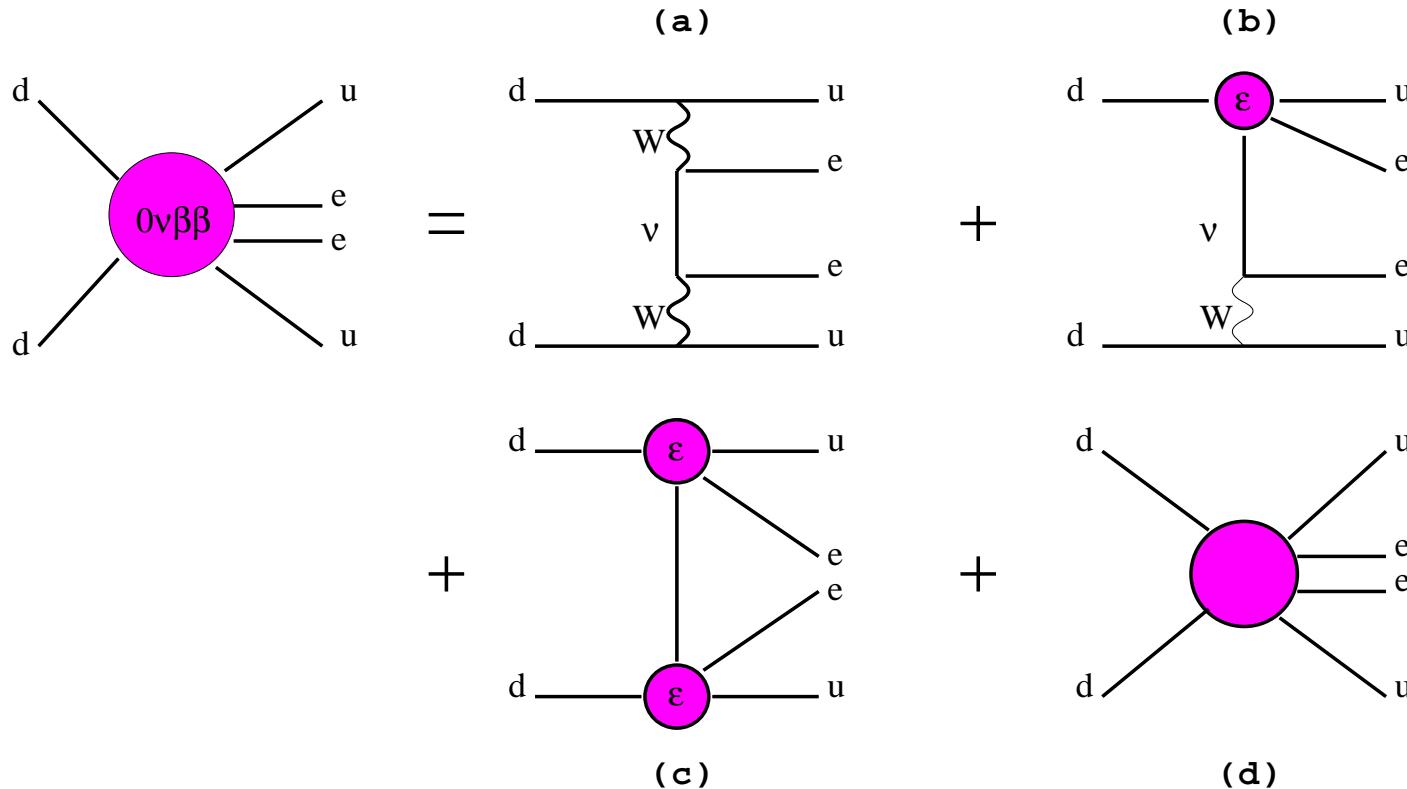
Where is the
neutrino???

From squark diagram and $T_{1/2}^{0\nu\beta\beta}(^{136}Xe) \geq 1.6 \times 10^{25}$ ys:

$$m_{\tilde{q}} \equiv m_{\tilde{g}} : \quad m_{\tilde{q}} \gtrsim 1.7 \left(\frac{\lambda'_{111}}{g_L} \right)^{2/5} \text{ TeV}$$

$0\nu\beta\beta$ schematically

Graphically:



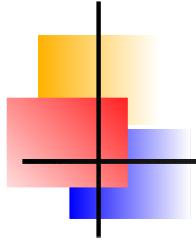
$$\Rightarrow (a) \text{ mass mechanism: } \langle m_\nu \rangle = \sum_j m_j U_{ej}^2$$

$$\Rightarrow (b) \text{ long-range part: } \epsilon \propto \frac{g_{eff}^2}{\Lambda_{eff}^2}$$

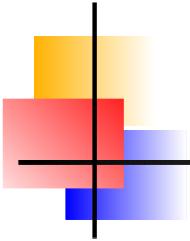
Päs et al. PLB453

$$\Rightarrow (d) \text{ short-range part: } \epsilon \propto \frac{g_{eff}^4}{\Lambda_{eff}^5} \Rightarrow \Lambda \gtrsim (1 - 3) \text{ TeV}$$

Päs et al. PLB498



$\langle m_\nu \rangle$ or BSM?



$\langle m_\nu \rangle$ or BSM?

(i) Using other experiments?

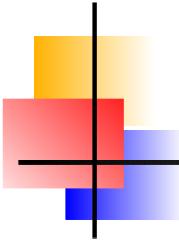
(i.1) KATRIN/Cosmology

Consistency of $|m_\nu|$ points to mass mechanism

Works only for $|m_\nu| \gtrsim 0.1(0.3)$ eV Cosmo (KATRIN)

(i.2) LHC

see below



$\langle m_\nu \rangle$ or BSM?

(i) Using other experiments?

(i.1) KATRIN/Cosmology

Consistency of $|m_\nu|$ points to mass mechanism

Works only for $|m_\nu| \gtrsim 0.1(0.3)$ eV Cosmo (KATRIN)

(i.2) LHC

see below

(ii) Double beta decay data only?

(ii.1) Angular correlations

For LR-models: [Doi, Kotani & Takasugi, 1985](#),

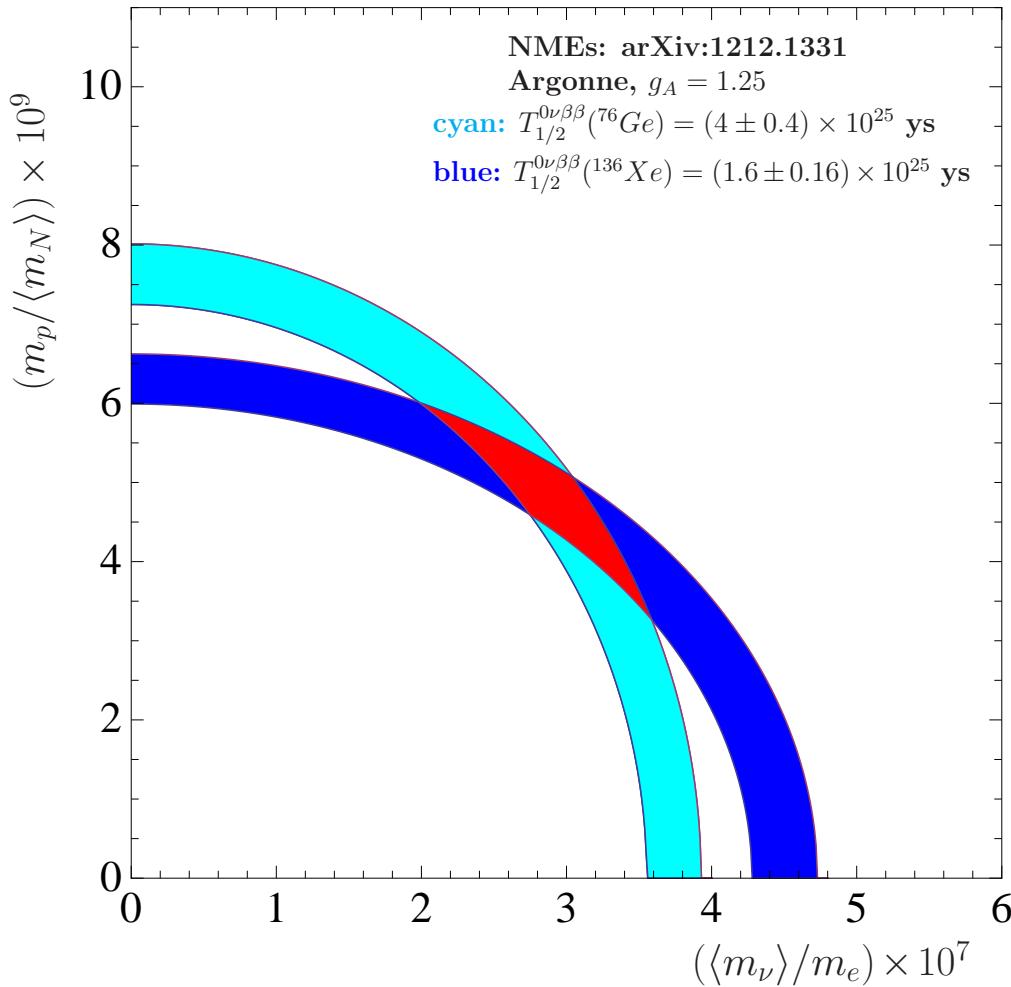
For general LI Lagrangian: [Ali, Borisov & Zhuridov, 2007](#)

(ii.2) Double beta plus decays

For LR-models: [Hirsch et al., 1994](#)

(ii.3) Compare rates for different isotopes?

More than one isotope?



Note:

Plot is not based on experimental data! For illustration only.

Simple idea:

$$T_{1/2} = G \left\{ (\epsilon_1 \mathcal{M}_1)^2 + (\epsilon_2 \mathcal{M}_2)^2 \right\}$$

Only one example:

$$\epsilon_1 = (\langle m_\nu \rangle / m_e)$$

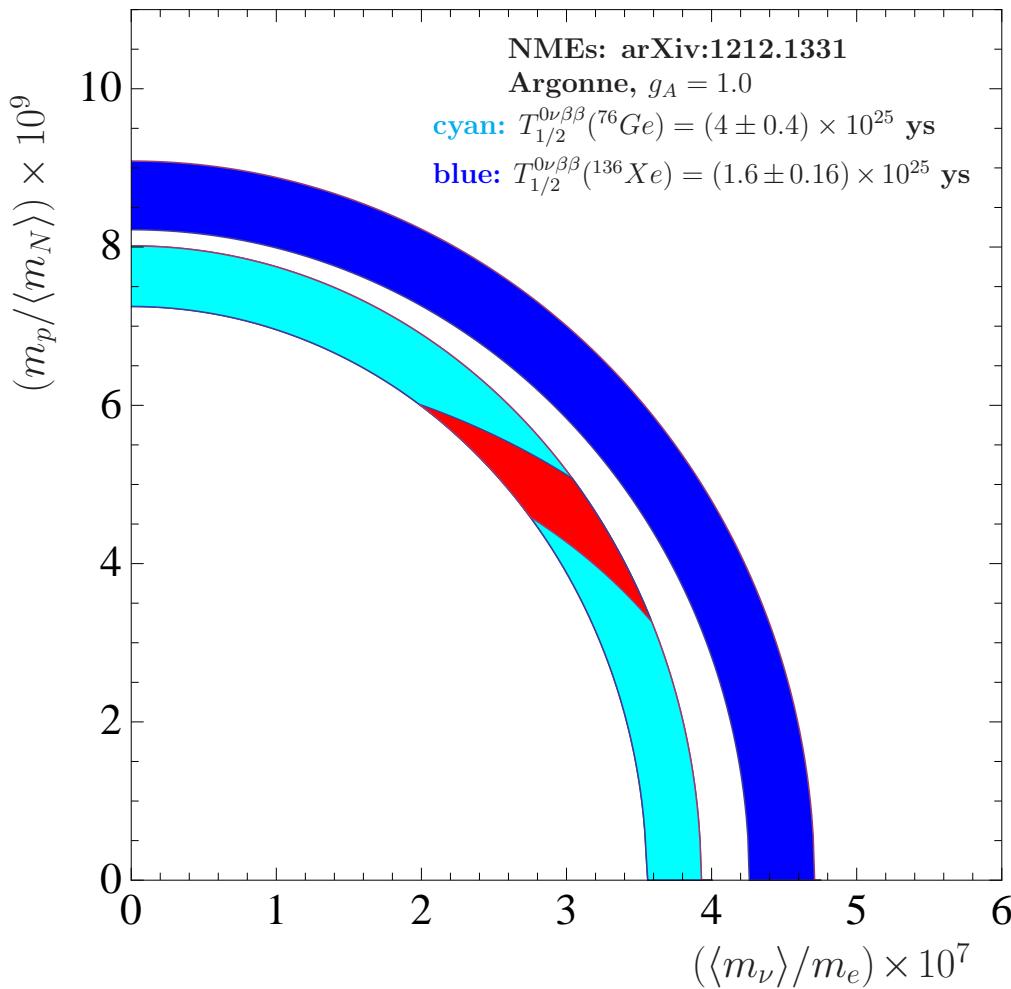
$$\epsilon_2 = (m_p / \langle m_N \rangle)$$

\mathcal{M}_i - matrix elements

Use two (or more) isotopes
solve for two unknowns ...

Consistency region
shown in red

More than one isotope?



Note:

Plot is not based on experimental data! For illustration only.

Simple idea:

$$T_{1/2} = G \left\{ (\epsilon_1 \mathcal{M}_1)^2 + (\epsilon_2 \mathcal{M}_2)^2 \right\}$$

Only one example:

$$\epsilon_1 = (\langle m_\nu \rangle / m_e)$$

$$\epsilon_2 = (m_p / \langle m_N \rangle)$$

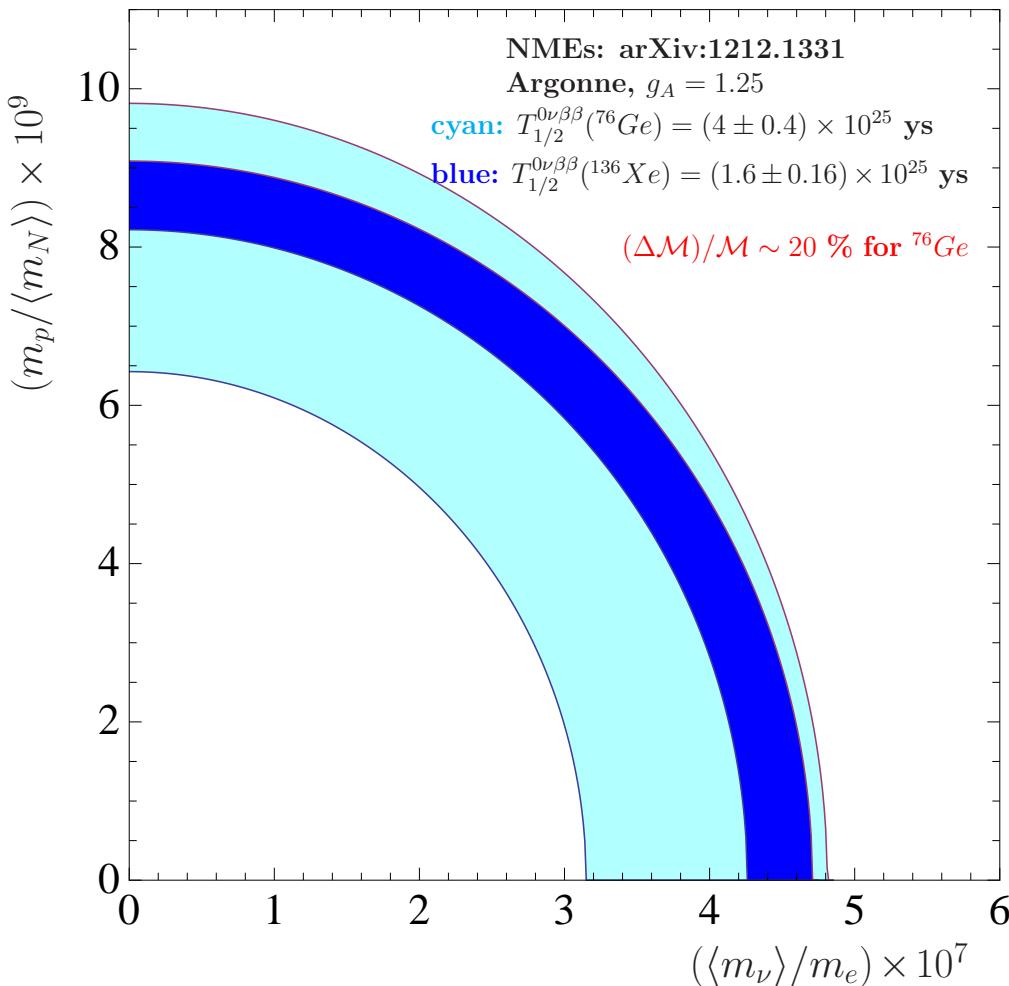
\mathcal{M}_i - matrix elements

Use two (or more) isotopes
solve for two unknowns ...

No overlap for exactly
same numbers, except:

\mathcal{M}_i !

More than one isotope?

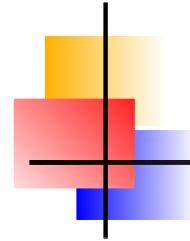


Same numbers except:

Arbitrary error for:
 $(\Delta M)/M \sim 20 \% \text{ for } ^{76}\text{Ge}$

Different mechanisms in different nuclei lead to (5-25) % differences, much smaller than typical error (ΔM)

Conclusion:
Better M needed!



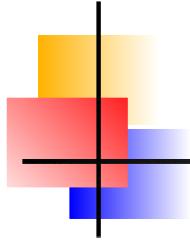
II.

General decomposition:

$d = 9~0\nu\beta\beta$ operator

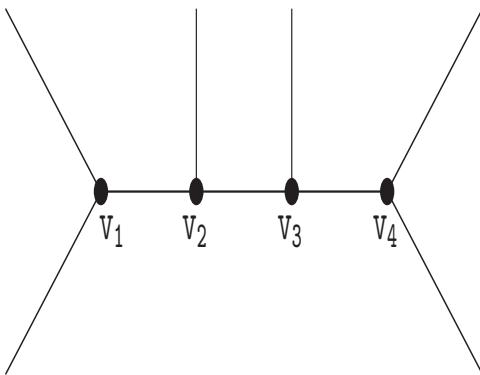
$$\mathcal{A}_{0\nu\beta\beta} \propto \frac{1}{\Lambda^5} (\bar{u}\bar{u}dd\bar{e}\bar{e})$$

See also poster by T. Ota

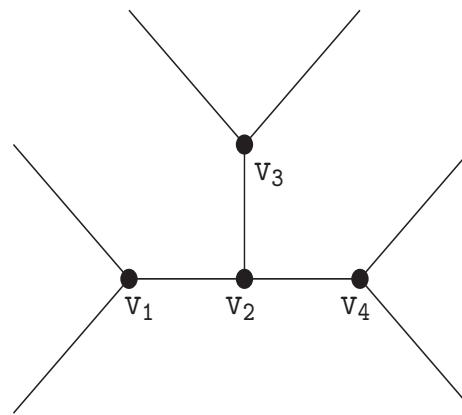


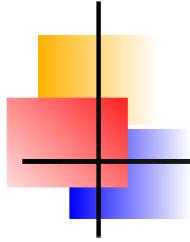
Tree-level topologies

Topology-I:



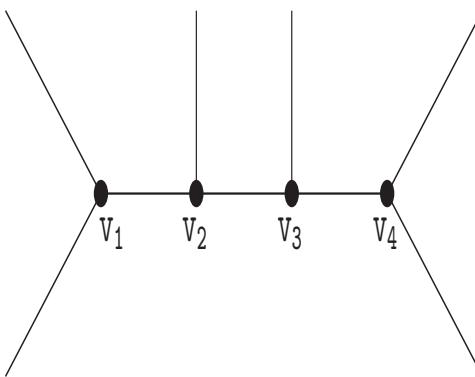
Topology-II:



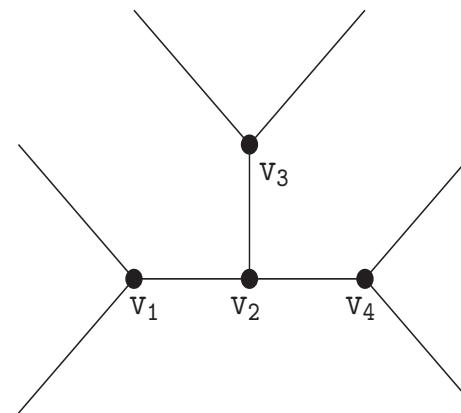


Tree-level topologies

Topology-I:

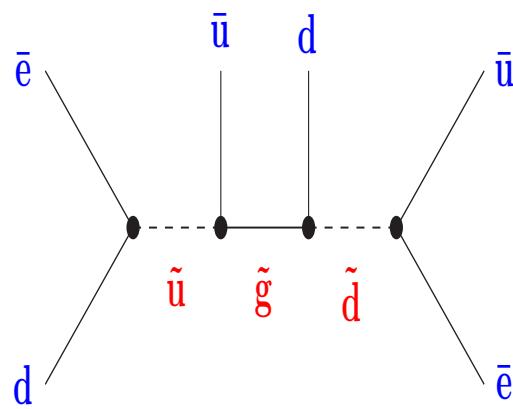


Topology-II:

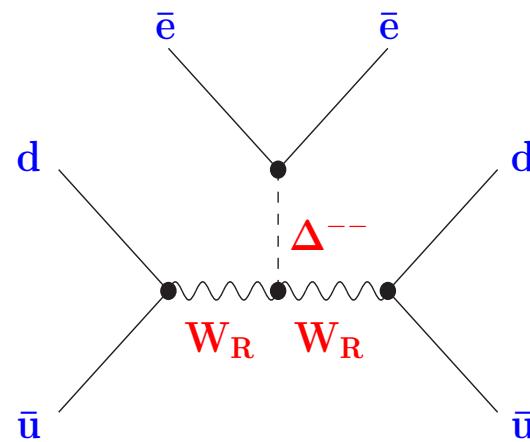


Examples:

RPV squark exchange:



LR symmetric model:



T-I: Decomposition

#	Decomposition	Mediator ($Q_{\text{em}}, SU(3)_c$)		
		S or V_ρ	ψ	S' or V'_ρ
1-i	$(\bar{u}d)(\bar{e})(\bar{e})(\bar{u}d)$	$(+1, \mathbf{1} \oplus \mathbf{8})$	$(0, \mathbf{1} \oplus \mathbf{8})$	$(-1, \mathbf{1} \oplus \mathbf{8})$
1-ii-a	$(\bar{u}d)(\bar{u})(d)(\bar{e}\bar{e})$	$(+1, \mathbf{1} \oplus \mathbf{8})$	$(+5/3, \mathbf{3})$	$(+2, \mathbf{1})$
1-ii-b	$(\bar{u}d)(d)(\bar{u})(\bar{e}\bar{e})$	$(+1, \mathbf{1} \oplus \mathbf{8})$	$(+4/3, \overline{\mathbf{3}})$	$(+2, \mathbf{1})$
2-i-a	$(\bar{u}d)(d)(\bar{e})(\bar{u}\bar{e})$	$(+1, \mathbf{1} \oplus \mathbf{8})$	$(+4/3, \overline{\mathbf{3}})$	$(+1/3, \overline{\mathbf{3}})$
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2-iii-a	$(d\bar{e})(\bar{u})(d)(\bar{u}\bar{e})$	$(-2/3, \overline{\mathbf{3}})$	$(0, \mathbf{1} \oplus \mathbf{8})$	$(+1/3, \overline{\mathbf{3}})$
2-iii-b	$(d\bar{e})(d)(\bar{u})(\bar{u}\bar{e})$	$(-2/3, \overline{\mathbf{3}})$	$(-1/3, \mathbf{3}_a \oplus \overline{\mathbf{6}}_s)$	$(+1/3, \overline{\mathbf{3}})$
3-i	$(\bar{u}\bar{u})(\bar{e})(\bar{e})(dd)$	$(+4/3, \overline{\mathbf{3}}_a \oplus \mathbf{6}_s)$	$(+1/3, \overline{\mathbf{3}}_a \oplus \mathbf{6}_s)$	$(-2/3, \overline{\mathbf{3}}_a \oplus \mathbf{6}_s)$
3-ii	$(\bar{u}\bar{u})(d)(d)(\bar{e}\bar{e})$	$(+4/3, \overline{\mathbf{3}}_a \oplus \mathbf{6}_s)$	$(+5/3, \mathbf{3})$	$(+2, \mathbf{1})$
3-iii	$(dd)(\bar{u})(\bar{u})(\bar{e}\bar{e})$	$(+2/3, \mathbf{3}_a \oplus \overline{\mathbf{6}}_s)$	$(+4/3, \overline{\mathbf{3}})$	$(+2, \mathbf{1})$
4-i	$(d\bar{e})(\bar{u})(\bar{u})(d\bar{e})$	$(-2/3, \overline{\mathbf{3}})$	$(0, \mathbf{1} \oplus \mathbf{8})$	$(+2/3, \mathbf{3})$
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18 decompositions
in total

× SFS, VFS and VFV

× # of different
chirality insertions

P_L and P_R

Table from:
[Bonnet et al.](#)
[JHEP03 \(2013\) 055](#)

T-I: Decomposition

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⇐ Mass mechanism

T-I: Decomposition

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2-iii-a	$(d\bar{e})(\bar{u})(d)(\bar{u}\bar{e})$	$(-2/3, \overline{\mathbf{3}})$	$(\mathbf{0}, \mathbf{1} \oplus \mathbf{8})$	$(+1/3, \overline{\mathbf{3}})$	$\Leftarrow \tilde{u} - \chi/\tilde{g} - \tilde{d}$
2-iii-b	$(d\bar{e})(d)(\bar{u})(\bar{u}\bar{e})$	$(-2/3, \overline{\mathbf{3}})$	$(-1/3, \mathbf{3}_a \oplus \overline{\mathbf{6}}_s)$	$(+1/3, \overline{\mathbf{3}})$	
3-i	$(\bar{u}\bar{u})(\bar{e})(\bar{e})(dd)$	$(+4/3, \overline{\mathbf{3}}_a \oplus \mathbf{6}_s)$	$(+1/3, \overline{\mathbf{3}}_a \oplus \mathbf{6}_s)$	$(-2/3, \overline{\mathbf{3}}_a \oplus \mathbf{6}_s)$	
3-ii	$(\bar{u}\bar{u})(d)(d)(\bar{e}\bar{e})$	$(+4/3, \overline{\mathbf{3}}_a \oplus \mathbf{6}_s)$	$(+5/3, \mathbf{3})$	$(+2, \mathbf{1})$	
3-iii	$(dd)(\bar{u})(\bar{u})(\bar{e}\bar{e})$	$(+2/3, \mathbf{3}_a \oplus \overline{\mathbf{6}}_s)$	$(+4/3, \overline{\mathbf{3}})$	$(+2, \mathbf{1})$	
4-i	$(d\bar{e})(\bar{u})(\bar{u})(d\bar{e})$	$(-2/3, \overline{\mathbf{3}})$	$(\mathbf{0}, \mathbf{1} \oplus \mathbf{8})$	$(+2/3, \mathbf{3})$	$\Leftarrow \tilde{u} - \chi/\tilde{g} - \tilde{u}$
4-ii-a	$(\bar{u}\bar{u})(d)(\bar{e})(d\bar{e})$	$(+4/3, \overline{\mathbf{3}}_a \oplus \mathbf{6}_s)$	$(+5/3, \mathbf{3})$	$(+2/3, \mathbf{3})$	
4-ii-b	$(\bar{u}\bar{u})(\bar{e})(d)(d\bar{e})$	$(+4/3, \overline{\mathbf{3}}_a \oplus \mathbf{6}_s)$	$(+1/3, \overline{\mathbf{3}}_a \oplus \mathbf{6}_s)$	$(+2/3, \mathbf{3})$	
5-i	$(\bar{u}\bar{e})(d)(d)(\bar{u}\bar{e})$	$(-1/3, \mathbf{3})$	$(\mathbf{0}, \mathbf{1} \oplus \mathbf{8})$	$(+1/3, \overline{\mathbf{3}})$	$\Leftarrow \tilde{d} - \chi/\tilde{g} - \tilde{d}$
5-ii-a	$(\bar{u}\bar{e})(\bar{u})(\bar{e})(dd)$	$(-1/3, \mathbf{3})$	$(+1/3, \overline{\mathbf{3}}_a \oplus \mathbf{6}_s)$	$(-2/3, \overline{\mathbf{3}}_a \oplus \mathbf{6}_s)$	
5-ii-b	$(\bar{u}\bar{e})(\bar{e})(\bar{u})(dd)$	$(-1/3, \mathbf{3})$	$(-4/3, \mathbf{3})$	$(-2/3, \overline{\mathbf{3}}_a \oplus \mathbf{6}_s)$	

T-I: Decomposition

#	Decomposition	Mediator ($Q_{\text{em}}, SU(3)_c$)		
		S or V_ρ	ψ	S' or V'_ρ
1-i	$(\bar{u}d)(\bar{e})(\bar{e})(\bar{u}d)$	$(+1, \mathbf{1} \oplus \mathbf{8})$	$(\mathbf{0}, \mathbf{1} \oplus \mathbf{8})$	$(-1, \mathbf{1} \oplus \mathbf{8})$
1-ii-a	$(\bar{u}d)(\bar{u})(d)(\bar{e}\bar{e})$	$(+1, \mathbf{1} \oplus \mathbf{8})$	$(+5/3, \mathbf{3})$	$(+2, \mathbf{1})$
1-ii-b	$(\bar{u}d)(d)(\bar{u})(\bar{e}\bar{e})$	$(+1, \mathbf{1} \oplus \mathbf{8})$	$(+4/3, \overline{\mathbf{3}})$	$(+2, \mathbf{1})$
2-i-a	$(\bar{u}d)(d)(\bar{e})(\bar{u}\bar{e})$	$(+1, \mathbf{1} \oplus \mathbf{8})$	$(+4/3, \overline{\mathbf{3}})$	$(+1/\mathbf{3}, \overline{\mathbf{3}})$
2-i-b	$(\bar{u}d)(\bar{e})(d)(\bar{u}\bar{e})$	$(+1, \mathbf{1} \oplus \mathbf{8})$	$(0, \mathbf{1} \oplus \mathbf{8})$	$(+1/\mathbf{3}, \overline{\mathbf{3}})$
2-ii-a	$(\bar{u}d)(\bar{u})(\bar{e})(d\bar{e})$	$(+1, \mathbf{1} \oplus \mathbf{8})$	$(+5/3, \mathbf{3})$	$(+2/\mathbf{3}, \mathbf{3})$
2-ii-b	$(\bar{u}d)(\bar{e})(\bar{u})(d\bar{e})$	$(+1, \mathbf{1} \oplus \mathbf{8})$	$(0, \mathbf{1} \oplus \mathbf{8})$	$(+2/\mathbf{3}, \mathbf{3})$
2-iii-a	$(d\bar{e})(\bar{u})(d)(\bar{u}\bar{e})$	$(-2/3, \overline{\mathbf{3}})$	$(0, \mathbf{1} \oplus \mathbf{8})$	$(+1/\mathbf{3}, \overline{\mathbf{3}})$
2-iii-b	$(d\bar{e})(d)(\bar{u})(\bar{u}\bar{e})$	$(-2/3, \overline{\mathbf{3}})$	$(-1/3, \mathbf{3}_a \oplus \overline{\mathbf{6}}_s)$	$(+1/\mathbf{3}, \overline{\mathbf{3}})$
3-i	$(\bar{u}\bar{u})(\bar{e})(\bar{e})(dd)$	$(+4/3, \overline{\mathbf{3}}_a \oplus \mathbf{6}_s)$	$(+1/3, \overline{\mathbf{3}}_a \oplus \mathbf{6}_s)$	$(-2/3, \overline{\mathbf{3}}_a \oplus \mathbf{6}_s)$
3-ii	$(\bar{u}\bar{u})(d)(d)(\bar{e}\bar{e})$	$(+4/3, \overline{\mathbf{3}}_a \oplus \mathbf{6}_s)$	$(+5/3, \mathbf{3})$	$(+2, \mathbf{1})$
3-iii	$(dd)(\bar{u})(\bar{u})(\bar{e}\bar{e})$	$(+2/3, \mathbf{3}_a \oplus \overline{\mathbf{6}}_s)$	$(+4/3, \overline{\mathbf{3}})$	$(+2, \mathbf{1})$
4-i	$(d\bar{e})(\bar{u})(\bar{u})(d\bar{e})$	$(-2/3, \overline{\mathbf{3}})$	$(0, \mathbf{1} \oplus \mathbf{8})$	$(+2/\mathbf{3}, \mathbf{3})$
4-ii-a	$(\bar{u}\bar{u})(d)(\bar{e})(d\bar{e})$	$(+4/3, \overline{\mathbf{3}}_a \oplus \mathbf{6}_s)$	$(+5/3, \mathbf{3})$	$(+2/\mathbf{3}, \mathbf{3})$
4-ii-b	$(\bar{u}\bar{u})(\bar{e})(d)(d\bar{e})$	$(+4/3, \overline{\mathbf{3}}_a \oplus \mathbf{6}_s)$	$(+1/3, \overline{\mathbf{3}}_a \oplus \mathbf{6}_s)$	$(+2/\mathbf{3}, \mathbf{3})$
5-i	$(\bar{u}\bar{e})(d)(d)(\bar{u}\bar{e})$	$(-1/3, \mathbf{3})$	$(0, \mathbf{1} \oplus \mathbf{8})$	$(+1/\mathbf{3}, \overline{\mathbf{3}})$
5-ii-a	$(\bar{u}\bar{e})(\bar{u})(\bar{e})(dd)$	$(-1/3, \mathbf{3})$	$(+1/3, \overline{\mathbf{3}}_a \oplus \mathbf{6}_s)$	$(-2/3, \overline{\mathbf{3}}_a \oplus \mathbf{6}_s)$
5-ii-b	$(\bar{u}\bar{e})(\bar{e})(\bar{u})(dd)$	$(-1/3, \mathbf{3})$	$(-4/3, \mathbf{3})$	$(-2/3, \overline{\mathbf{3}}_a \oplus \mathbf{6}_s)$

Leptoquarks

⇐ Long-range LQ

⇐ Long-range LQ

⇐ Angel et al.

JHEP 1310, 2013

T-I: Decomposition

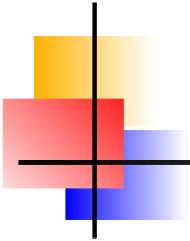
Mediator ($Q_{\text{em}}, SU(3)_c$)				
#	Decomposition	S or V_ρ	ψ	S' or V'_ρ
1-i	$(\bar{u}d)(\bar{e})(\bar{e})(\bar{u}d)$	$(+1, 1 \oplus 8)$	$(0, 1 \oplus 8)$	$(-1, 1 \oplus 8)$
1-ii-a	$(\bar{u}d)(\bar{u})(d)(\bar{e}\bar{e})$	$(+1, 1 \oplus 8)$	$(+5/3, \mathbf{3})$	$(+2, \mathbf{1})$
1-ii-b	$(\bar{u}d)(d)(\bar{u})(\bar{e}\bar{e})$	$(+1, 1 \oplus 8)$	$(+4/3, \overline{\mathbf{3}})$	$(+2, \mathbf{1})$
2-i-a	$(\bar{u}d)(d)(\bar{e})(\bar{u}\bar{e})$	$(+1, 1 \oplus 8)$	$(+4/3, \overline{\mathbf{3}})$	$(+1/3, \overline{\mathbf{3}})$
2-i-b	$(\bar{u}d)(\bar{e})(d)(\bar{u}\bar{e})$	$(+1, 1 \oplus 8)$	$(0, 1 \oplus 8)$	$(+1/3, \overline{\mathbf{3}})$
2-ii-a	$(\bar{u}d)(\bar{u})(\bar{e})(d\bar{e})$	$(+1, 1 \oplus 8)$	$(+5/3, \mathbf{3})$	$(+2/3, \mathbf{3})$
2-ii-b	$(\bar{u}d)(\bar{e})(\bar{u})(d\bar{e})$	$(+1, 1 \oplus 8)$	$(0, 1 \oplus 8)$	$(+2/3, \mathbf{3})$
2-iii-a	$(d\bar{e})(\bar{u})(d)(\bar{u}\bar{e})$	$(-2/3, \overline{\mathbf{3}})$	$(0, 1 \oplus 8)$	$(+1/3, \overline{\mathbf{3}})$
2-iii-b	$(d\bar{e})(d)(\bar{u})(\bar{u}\bar{e})$	$(-2/3, \overline{\mathbf{3}})$	$(-1/3, \mathbf{3}_a \oplus \overline{\mathbf{6}}_s)$	$(+1/3, \overline{\mathbf{3}})$
3-i	$(\bar{u}\bar{u})(\bar{e})(\bar{e})(dd)$	$(+4/3, \overline{\mathbf{3}}_a \oplus \mathbf{6}_s)$	$(+1/3, \overline{\mathbf{3}}_a \oplus \mathbf{6}_s)$	$(-2/3, \overline{\mathbf{3}}_a \oplus \mathbf{6}_s)$
3-ii	$(\bar{u}\bar{u})(d)(d)(\bar{e}\bar{e})$	$(+4/3, \overline{\mathbf{3}}_a \oplus \mathbf{6}_s)$	$(+5/3, \mathbf{3})$	$(+2, \mathbf{1})$
3-iii	$(dd)(\bar{u})(\bar{u})(\bar{e}\bar{e})$	$(+2/3, \mathbf{3}_a \oplus \overline{\mathbf{6}}_s)$	$(+4/3, \overline{\mathbf{3}})$	$(+2, \mathbf{1})$
4-i	$(d\bar{e})(\bar{u})(\bar{u})(d\bar{e})$	$(-2/3, \overline{\mathbf{3}})$	$(0, 1 \oplus 8)$	$(+2/3, \mathbf{3})$
4-ii-a	$(\bar{u}\bar{u})(d)(\bar{e})(d\bar{e})$	$(+4/3, \overline{\mathbf{3}}_a \oplus \mathbf{6}_s)$	$(+5/3, \mathbf{3})$	$(+2/3, \mathbf{3})$
4-ii-b	$(\bar{u}\bar{u})(\bar{e})(d)(d\bar{e})$	$(+4/3, \overline{\mathbf{3}}_a \oplus \mathbf{6}_s)$	$(+1/3, \overline{\mathbf{3}}_a \oplus \mathbf{6}_s)$	$(+2/3, \mathbf{3})$
5-i	$(\bar{u}\bar{e})(d)(d)(\bar{u}\bar{e})$	$(-1/3, \mathbf{3})$	$(0, 1 \oplus 8)$	$(+1/3, \overline{\mathbf{3}})$
5-ii-a	$(\bar{u}\bar{e})(\bar{u})(\bar{e})(dd)$	$(-1/3, \mathbf{3})$	$(+1/3, \overline{\mathbf{3}}_a \oplus \mathbf{6}_s)$	$(-2/3, \overline{\mathbf{3}}_a \oplus \mathbf{6}_s)$
5-ii-b	$(\bar{u}\bar{e})(\bar{e})(\bar{u})(dd)$	$(-1/3, \mathbf{3})$	$(-4/3, \mathbf{3})$	$(-2/3, \overline{\mathbf{3}}_a \oplus \mathbf{6}_s)$

Di-quarks

T-I: Decomposition

#	Decomposition	Mediator ($Q_{\text{em}}, SU(3)_c$)		
		S or V_ρ	ψ	S' or V'_ρ
1-i	$(\bar{u}d)(\bar{e})(\bar{e})(\bar{u}d)$	$(+1, 1 \oplus 8)$	$(0, 1 \oplus 8)$	$(-1, 1 \oplus 8)$
1-ii-a	$(\bar{u}d)(\bar{u})(d)(\bar{e}\bar{e})$	$(+1, 1 \oplus 8)$	$(+5/3, 3)$	$(+2, 1)$
1-ii-b	$(\bar{u}d)(d)(\bar{u})(\bar{e}\bar{e})$	$(+1, 1 \oplus 8)$	$(+4/3, \bar{3})$	$(+2, 1)$
2-i-a	$(\bar{u}d)(d)(\bar{e})(\bar{u}\bar{e})$	$(+1, 1 \oplus 8)$	$(+4/3, \bar{3})$	$(+1/3, \bar{3})$
2-i-b	$(\bar{u}d)(\bar{e})(d)(\bar{u}\bar{e})$	$(+1, 1 \oplus 8)$	$(0, 1 \oplus 8)$	$(+1/3, \bar{3})$
2-ii-a	$(\bar{u}d)(\bar{u})(\bar{e})(d\bar{e})$	$(+1, 1 \oplus 8)$	$(+5/3, 3)$	$(+2/3, 3)$
2-ii-b	$(\bar{u}d)(\bar{e})(\bar{u})(d\bar{e})$	$(+1, 1 \oplus 8)$	$(0, 1 \oplus 8)$	$(+2/3, 3)$
2-iii-a	$(d\bar{e})(\bar{u})(d)(\bar{u}\bar{e})$	$(-2/3, \bar{3})$	$(0, 1 \oplus 8)$	$(+1/3, \bar{3})$
2-iii-b	$(d\bar{e})(d)(\bar{u})(\bar{u}\bar{e})$	$(-2/3, \bar{3})$	$(-1/3, \mathbf{3}_a \oplus \bar{\mathbf{6}}_s)$	$(+1/3, \bar{3})$
3-i	$(\bar{u}\bar{u})(\bar{e})(\bar{e})(dd)$	$(+4/3, \bar{3}_a \oplus \mathbf{6}_s)$	$(+1/3, \bar{3}_a \oplus \mathbf{6}_s)$	$(-2/3, \bar{3}_a \oplus \mathbf{6}_s)$
3-ii	$(\bar{u}\bar{u})(d)(d)(\bar{e}\bar{e})$	$(+4/3, \bar{3}_a \oplus \mathbf{6}_s)$	$(+5/3, 3)$	$(+2, 1)$
3-iii	$(dd)(\bar{u})(\bar{u})(\bar{e}\bar{e})$	$(+2/3, \mathbf{3}_a \oplus \bar{\mathbf{6}}_s)$	$(+4/3, \bar{3})$	$(+2, 1)$
4-i	$(d\bar{e})(\bar{u})(\bar{u})(d\bar{e})$	$(-2/3, \bar{3})$	$(0, 1 \oplus 8)$	$(+2/3, 3)$
4-ii-a	$(\bar{u}\bar{u})(d)(\bar{e})(d\bar{e})$	$(+4/3, \bar{3}_a \oplus \mathbf{6}_s)$	$(+5/3, 3)$	$(+2/3, 3)$
4-ii-b	$(\bar{u}\bar{u})(\bar{e})(d)(d\bar{e})$	$(+4/3, \bar{3}_a \oplus \mathbf{6}_s)$	$(+1/3, \bar{3}_a \oplus \mathbf{6}_s)$	$(+2/3, 3)$
5-i	$(\bar{u}\bar{e})(d)(d)(\bar{u}\bar{e})$	$(-1/3, 3)$	$(0, 1 \oplus 8)$	$(+1/3, \bar{3})$
5-ii-a	$(\bar{u}\bar{e})(\bar{u})(\bar{e})(dd)$	$(-1/3, 3)$	$(+1/3, \bar{3}_a \oplus \mathbf{6}_s)$	$(-2/3, \bar{3}_a \oplus \mathbf{6}_s)$
5-ii-b	$(\bar{u}\bar{e})(\bar{e})(\bar{u})(dd)$	$(-1/3, 3)$	$(-4/3, 3)$	$(-2/3, \bar{3}_a \oplus \mathbf{6}_s)$

Coloured fermions/
vector-like quarks



T-II: Decomposition

Bonnet et al.
JHEP03 (2013) 055

For completeness:

Mediator $(Q_{\text{em}}, SU(3)_c)$					
#	Decomposition	S or V_ρ	S' or V'_ρ	S'' or V''_ρ	
1	$(\bar{u}d)(\bar{u}d)(\bar{e}\bar{e})$	$(+1, \mathbf{1} \oplus \mathbf{8})$	$(+1, \mathbf{1} \oplus \mathbf{8})$	$(-2, \mathbf{1})$	$\Leftarrow \text{LR } \Delta^{--} \text{ (Rizzo, 1982)}$
2	$(\bar{u}d)(\bar{u}\bar{e})(\bar{e}d)$	$(+1, \mathbf{1} \oplus \mathbf{8})$	$(-1/3, \mathbf{3})$	$(-2/3, \overline{\mathbf{3}})$	
3	$(\bar{u}\bar{u})(dd)(\bar{e}\bar{e})$	$(+4/3, \overline{\mathbf{3}}_a \oplus \mathbf{6}_s)$	$(+2/3, \mathbf{3}_a \oplus \overline{\mathbf{6}}_s)$	$(-2, \mathbf{1})$	
4	$(\bar{u}\bar{u})(\bar{e}d)(\bar{e}d)$	$(+4/3, \overline{\mathbf{3}}_a \oplus \mathbf{6}_s)$	$(-2/3, \overline{\mathbf{3}})$	$(-2/3, \overline{\mathbf{3}})$	
5	$(\bar{u}\bar{e})(\bar{u}\bar{e})(dd)$	$(-1/3, \mathbf{3})$	$(-1/3, \mathbf{3})$	$(+2/3, \mathbf{3}_a \oplus \overline{\mathbf{6}}_s)$	

T-II: Decomposition

Bonnet et al.
JHEP03 (2013) 055

For completeness:

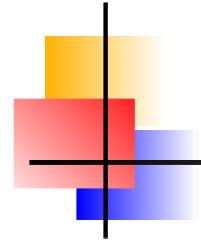
Mediator $(Q_{\text{em}}, SU(3)_c)$					
#	Decomposition	S or V_ρ	S' or V'_ρ	S'' or V''_ρ	
1	$(\bar{u}d)(\bar{u}d)(\bar{e}\bar{e})$	$(+1, 1 \oplus 8)$	$(+1, 1 \oplus 8)$	$(-2, 1)$	\Leftarrow LR Δ^{--} (Rizzo, 1982)
2	$(\bar{u}d)(\bar{u}\bar{e})(\bar{e}d)$	$(+1, 1 \oplus 8)$	$(-1/3, 3)$	$(-2/3, \bar{3})$	\Leftarrow (New) LQ
3	$(\bar{u}\bar{u})(dd)(\bar{e}\bar{e})$	$(+4/3, \bar{3}_a \oplus 6_s)$	$(+2/3, 3_a \oplus \bar{6}_s)$	$(-2, 1)$	\Leftarrow (New) DQ
4	$(\bar{u}\bar{u})(\bar{e}d)(\bar{e}d)$	$(+4/3, \bar{3}_a \oplus 6_s)$	$(-2/3, \bar{3})$	$(-2/3, \bar{3})$	\Leftarrow (New) LQ+DQ
5	$(\bar{u}\bar{e})(\bar{u}\bar{e})(dd)$	$(-1/3, 3)$	$(-1/3, 3)$	$(+2/3, 3_a \oplus \bar{6}_s)$	\Leftarrow P.-H. Gu, 2011 & Kohda et al., 2012

\Rightarrow Note: Same (five) new vectors/scalars but no exotic fermion:

S_{+1} - singly charged scalar (vector)

$S_{2/3}^{LQ}, S_{1/3}^{LQ}$ - leptoquarks

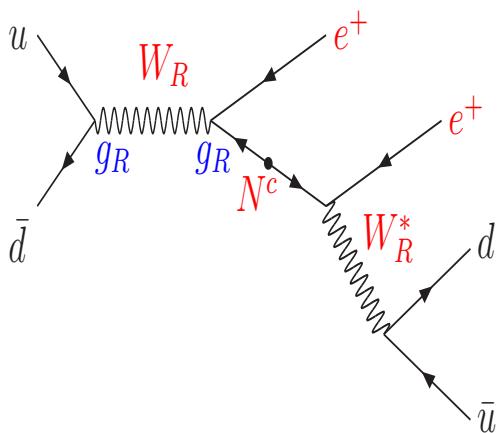
$S_{2/3}^{DQ}, S_{4/3}^{DQ}$ - “diquarks”



III.

LNV, $0\nu\beta\beta$ and the LHC

Example: W_R @ LHC

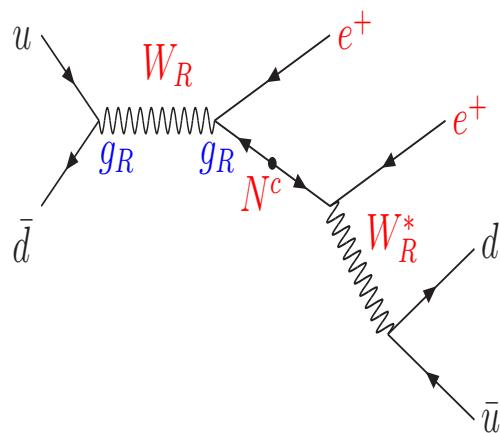


Keung & Senjanovic, 1983

Signal:

Same-sign and opposite-sign
di-lepton + jets, no \cancel{E}_T

Example: W_R @ LHC



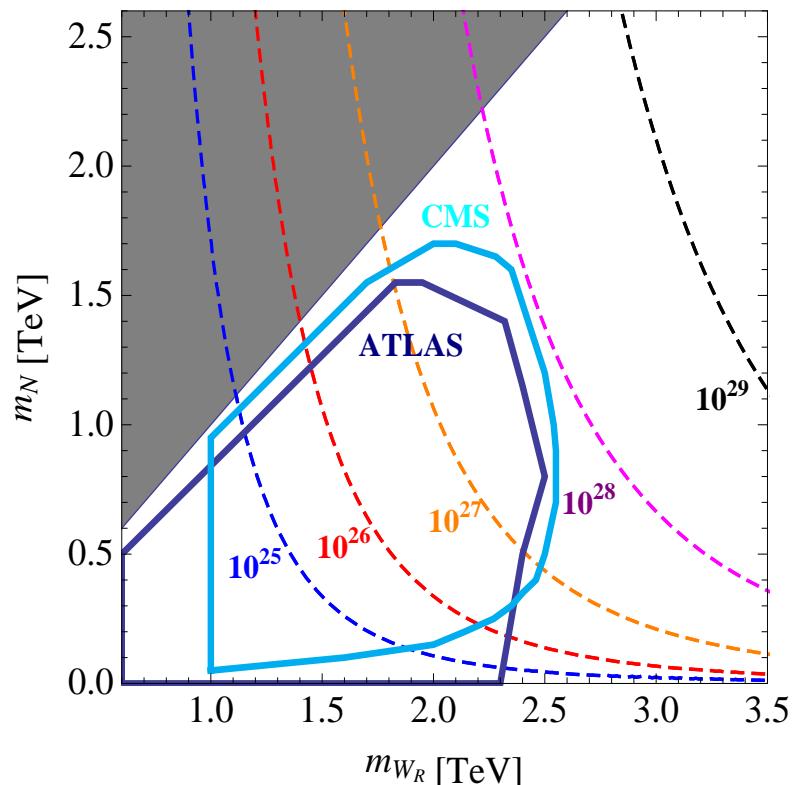
CMS (and ATLAS) with $\sqrt{s} = 8$ TeV:
 Non-observation gives
 stringent limits on
 short-range W_R diagrams
 for $0\nu\beta\beta$ decay.

Assumes: $g_R = g_L$!

Keung & Senjanovic, 1983

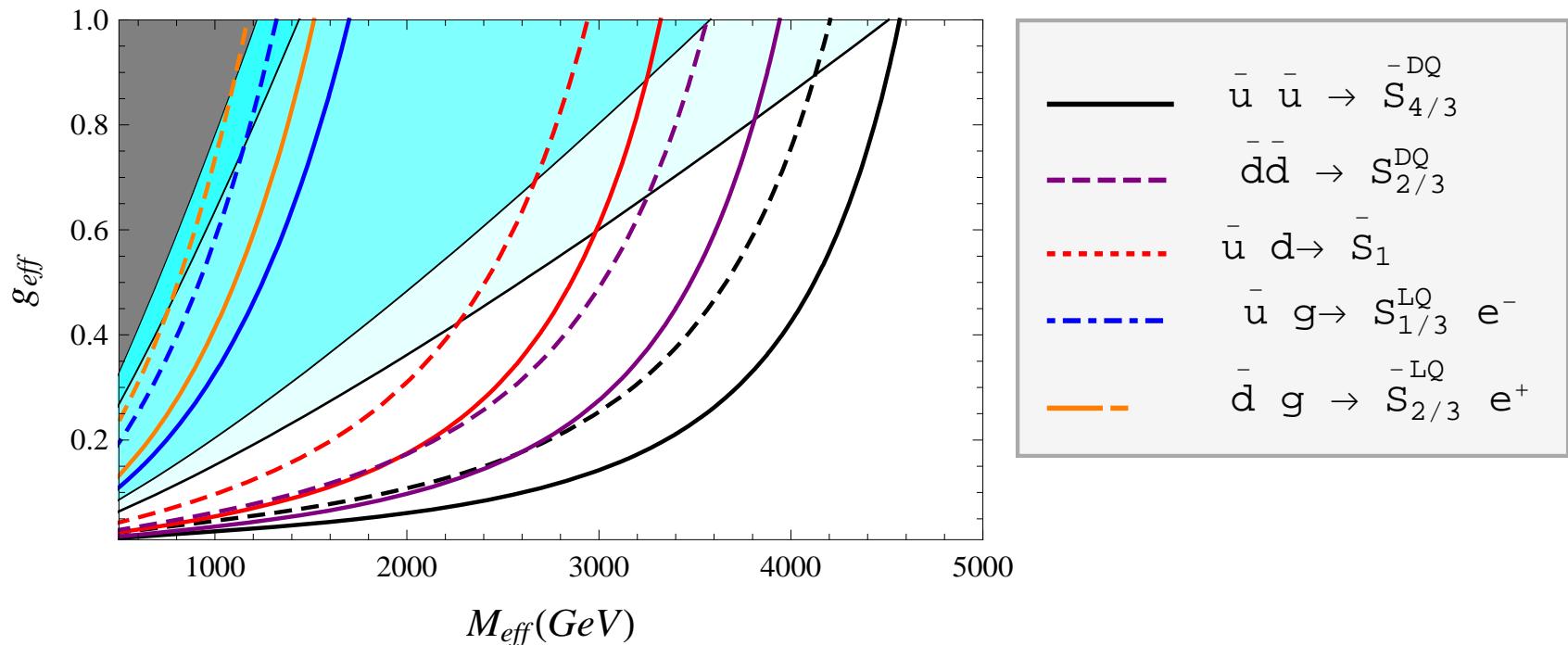
Signal:

Same-sign and opposite-sign
 di-lepton + jets, no \cancel{E}_T



Forecast for $\sqrt{s} = 14 \text{ TeV}$

J.C. Helo et al,
PRD88 (2013) 011901



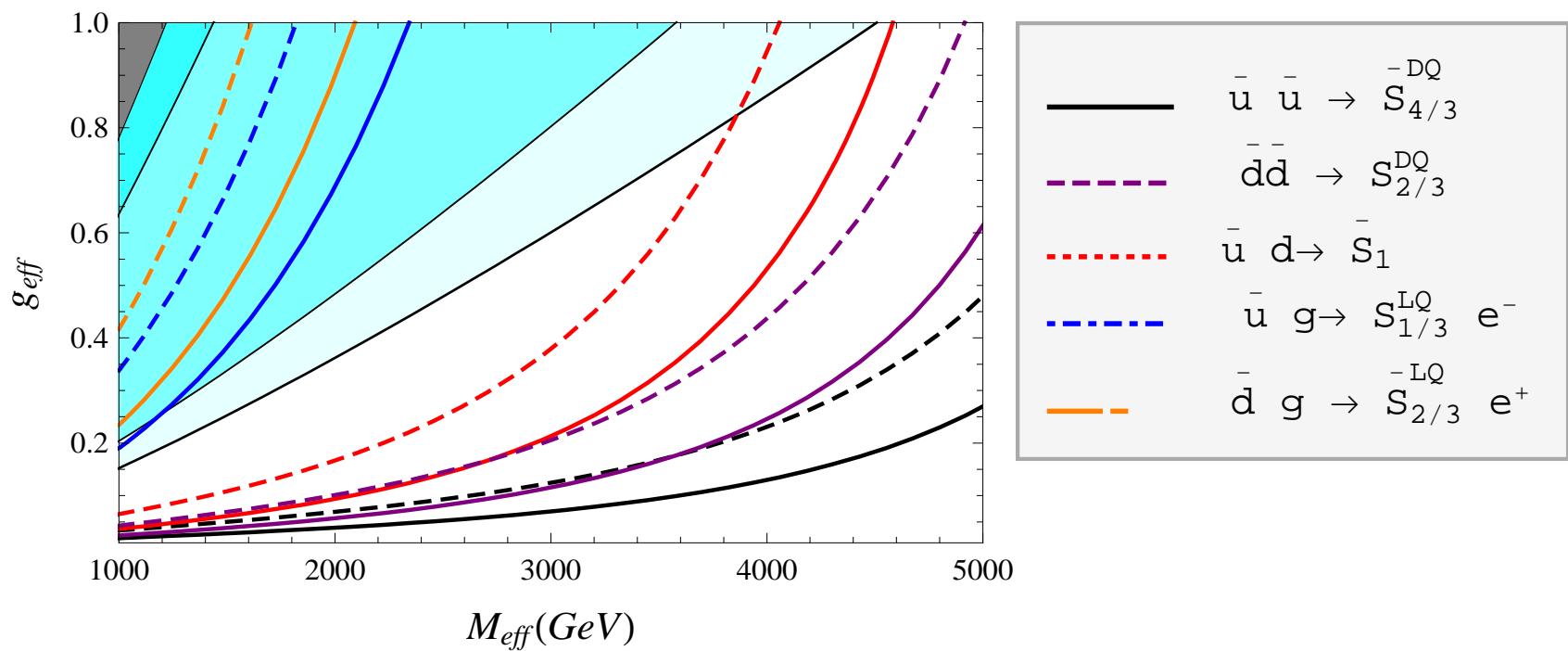
\Rightarrow Assumed upper limit on $\sigma(pp \rightarrow X)$: 10^{-2} fb

$\Rightarrow m_F = 200 \text{ GeV}$ (pessimistic case!)

\Rightarrow Full lines: $\text{Br} = 10^{-1}$, dashed lines $\text{Br} = 10^{-2}$

Forecast for $\sqrt{s} = 14 \text{ TeV}$

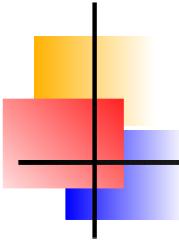
J.C. Helo et al,
PRD88 (2013) 011901



\Rightarrow Assumed upper limit on $\sigma(pp \rightarrow X)$: 10^{-2} fb

$\Rightarrow m_F = 1000 \text{ GeV}$ (realistic (?) case)

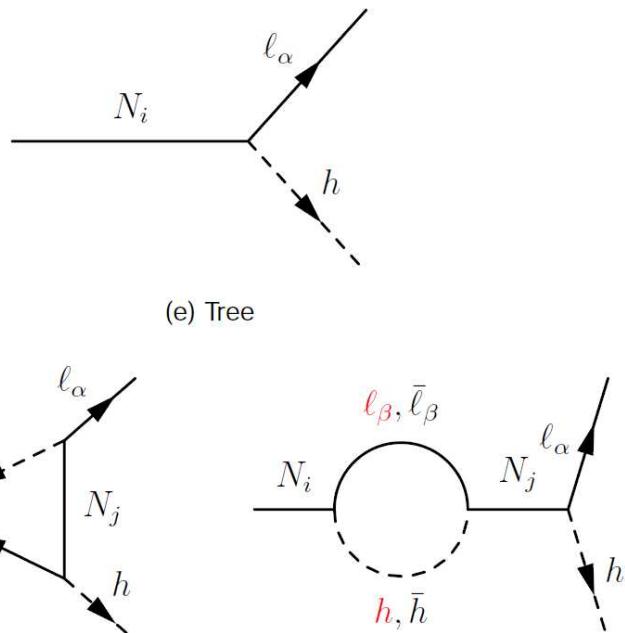
\Rightarrow Full lines: $\text{Br} = 10^{-1}$, dashed lines $\text{Br} = 10^{-2}$



Leptogenesis

Sakharov's conditions:

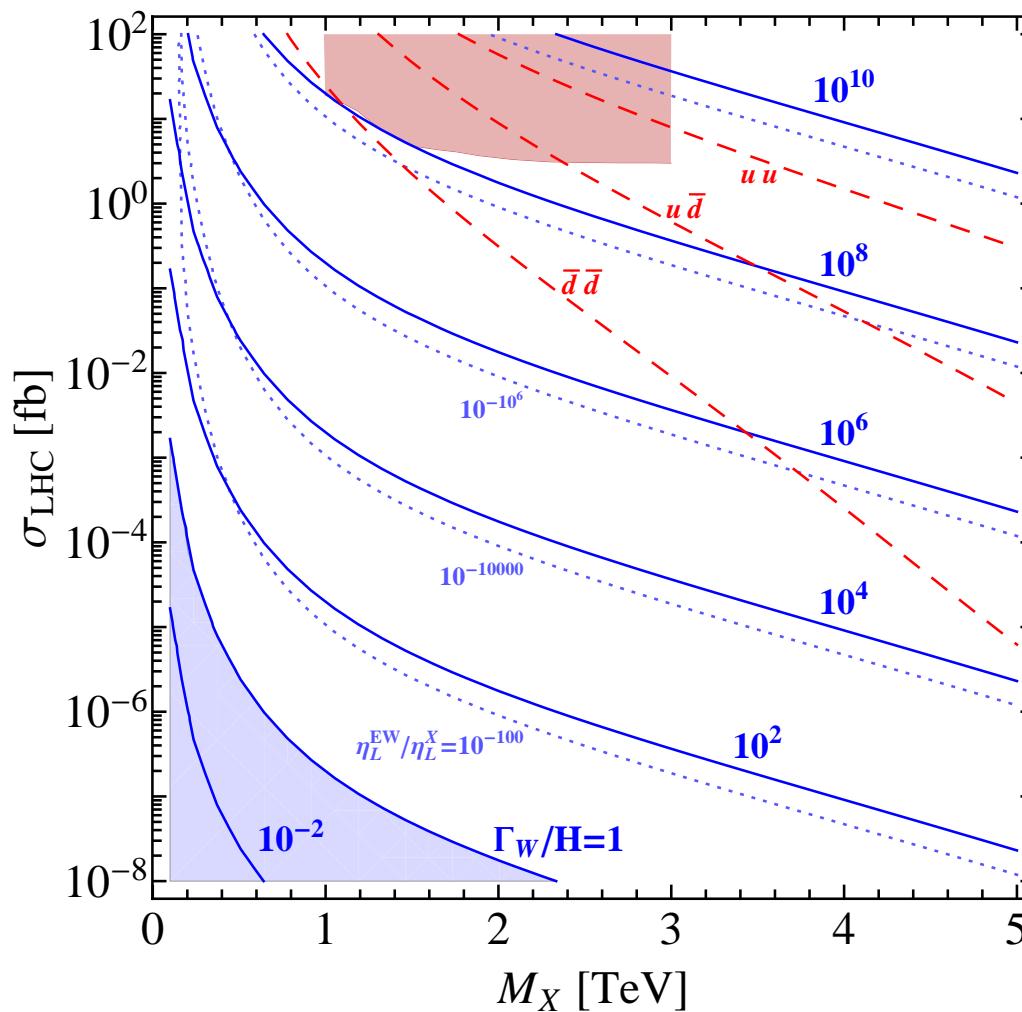
- (i) Baryon number violation
- (ii) C and CP violation
- (iii) **departure from thermal equilibrium**



In Leptogenesis:

- (i) Convert L to B through SM sphalerons
- (ii) CP violation through interference tree \leftrightarrow 1-loop
- (iii) **L out of equilibrium** via right-handed neutrino decay

Leptogenesis and LHC



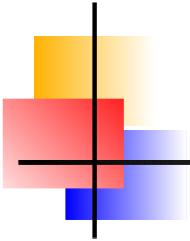
Deppisch, Hartz & Hirsch
arXiv:1312.4447
PRL, in press

Observation of
LNV @ LHC implies:
(High-scale) Leptogenesis
is ruled out!

blue lines:
washout factor Γ_W

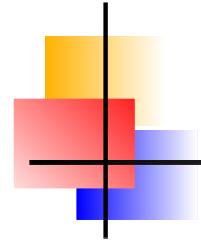
Loopholes???

- (i) Resonant LG with $m_N \ll m_X$?
- (ii) Hide LG in τ 's?

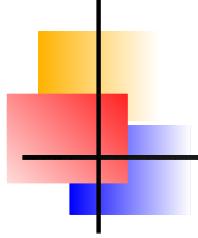


Conclusions

- ⇒ All models with lepton number violation contribute to $0\nu\beta\beta$ decay
- ⇒ Discovery of $0\nu\beta\beta$ decay \equiv Majorana neutrinos
- ⇒ IF $0\nu\beta\beta$ decay is discovered:
Which is the dominant mechanism?
 - $\langle m_\nu \rangle$ - consistency with other measurements
 - short range operators: by LHC!
 - long range \not{p} : Only $0\nu\beta\beta$ (?)
- ⇒ Need better NME!

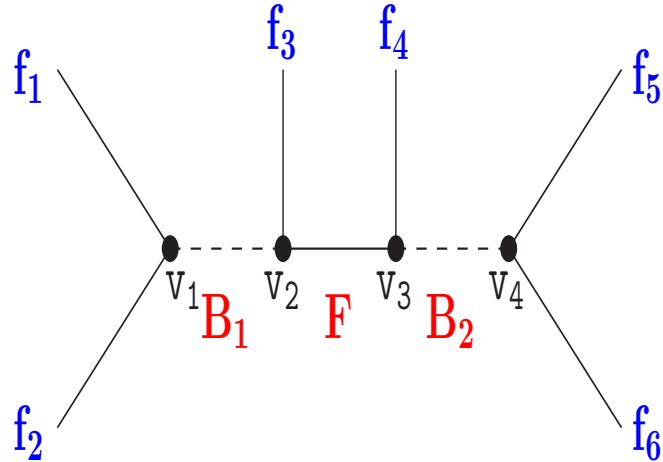


Backup slides



Comments on $0\nu\beta\beta$ versus LHC

$0\nu\beta\beta$ versus LHC



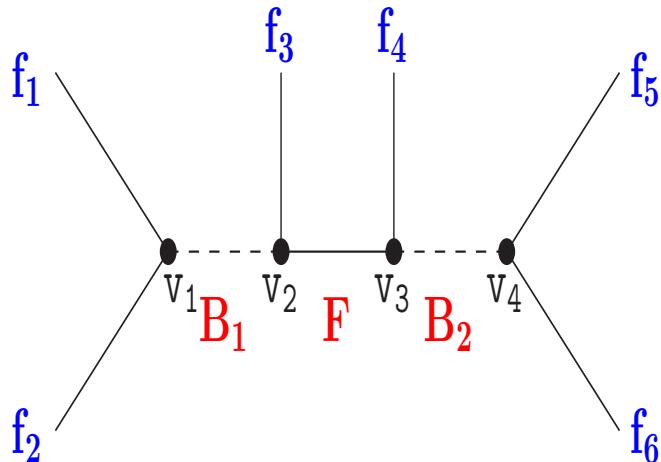
$$\mathcal{A}_I^{0\nu\beta\beta} \propto \frac{g_1 g_2 g_3 g_4}{m_{B_1}^2 m_F m_{B_2}^2}$$

Define:

$$g_{eff} = (g_1 g_2 g_3 g_4)^{1/4}$$

$$M_{eff} = (m_{B_1}^2 m_F m_{B_2}^2)^{1/5}$$

$0\nu\beta\beta$ versus LHC



$$\mathcal{A}_I^{0\nu\beta\beta} \propto \frac{g_1 g_2 g_3 g_4}{m_{B_1}^2 m_F m_{B_2}^2}$$

Define:

$$g_{eff} = (g_1 g_2 g_3 g_4)^{1/4}$$

$$M_{eff} = (m_{B_1}^2 m_F m_{B_2}^2)^{1/5}$$

⇒ Compare to LHC:

$$\# \text{events}(e^\pm e^\pm jj) : \sigma(pp \rightarrow B_1) \times Br(B_1 \rightarrow F + f_3) \times Br(F \rightarrow f_4 f_5 f_6)$$

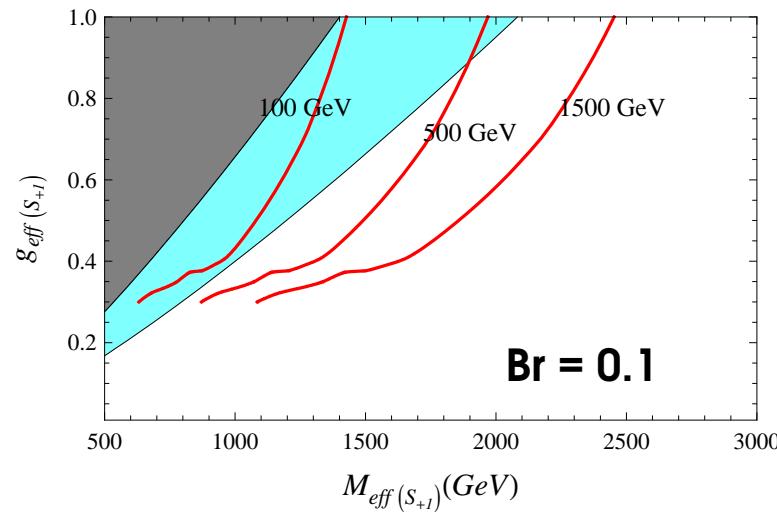
⇒ Heavy F , once produced on-shell, will decay

⇒ $\sigma(pp \rightarrow B_1)$ depends on m_{B_1} and g_1 , but not on m_{B_2} nor g_3, g_4

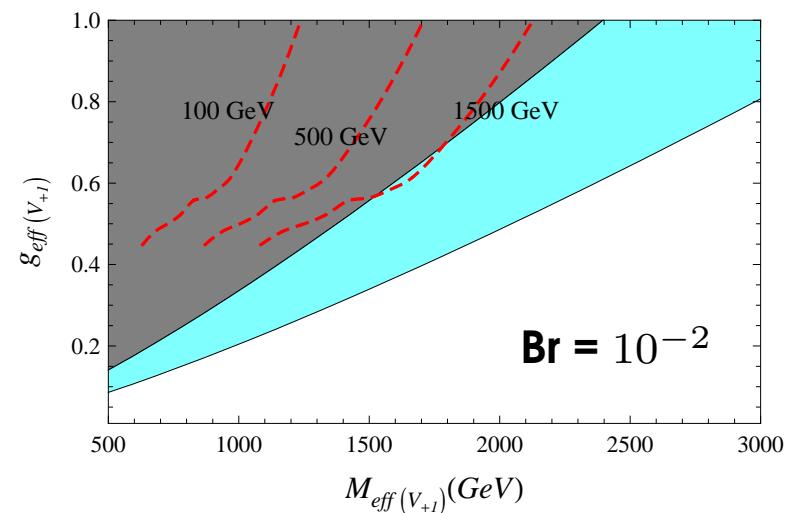
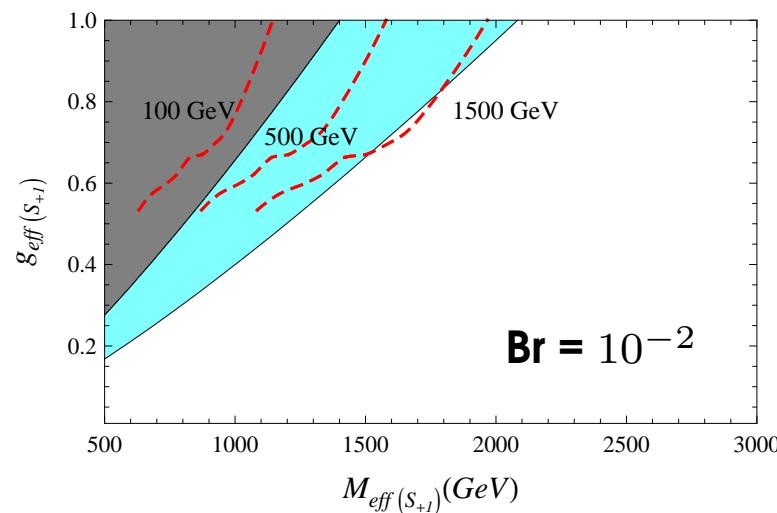
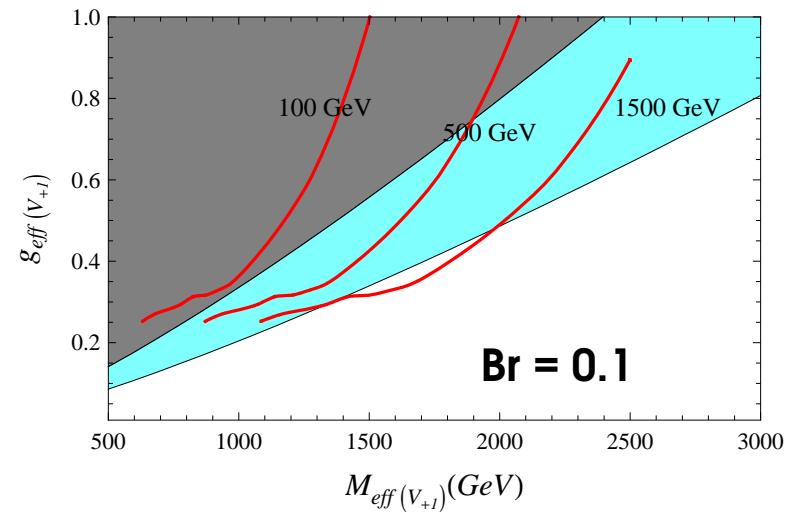
⇒ $Br(B_1 \rightarrow F + f_3)$ depends on m_{F_1} and g_2 , but not on m_{B_2} nor g_3, g_4

Status for $\sqrt{s} = 8 \text{ TeV}$

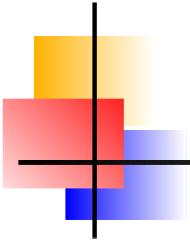
Case SFS:



Case VFV:



⇒ Red lines: CMS-EXO-12-017-pas upper limit



$(\Delta\mathcal{M})$ and short-range $0\nu\beta\beta$

$$\mathcal{A}_I^{0\nu\beta\beta} \propto \frac{g_1 g_2 g_3 g_4}{m_{B_1}^2 m_F m_{B_2}^2}$$

Define:

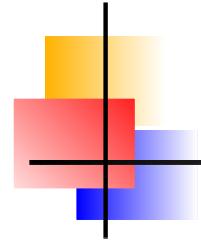
$$g_{eff} = (g_1 g_2 g_3 g_4)^{1/4}$$

$$M_{eff} = (m_{B_1}^2 m_F m_{B_2}^2)^{1/5}$$

Then:

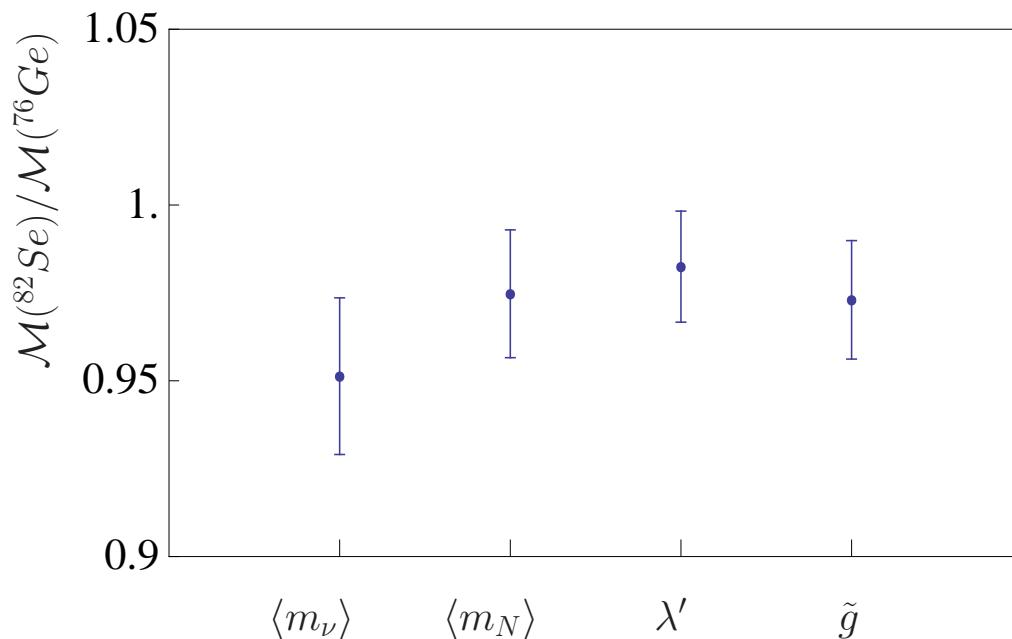
$$(\Delta M_{eff}) \propto (\Delta\mathcal{M})^{-1/5}$$

\Rightarrow For $(\Delta\mathcal{M}) \sim 2$ (3), $(\Delta M_{eff}) \sim 13\%$ (20%)



More comments on using different isotopes

Ratios of matrix elements



To distinguish:
Need different mechanisms
to have different NME ratios.

“Error bar” due to variation
of NMEs in Table 1 of 1212.1331

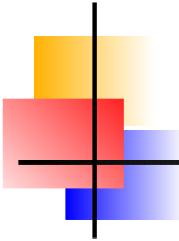
Plot shows ratio of matrix elements for different “mechanisms”, see 1212.1331:

$\langle m_\nu \rangle$ - Mass mechanism

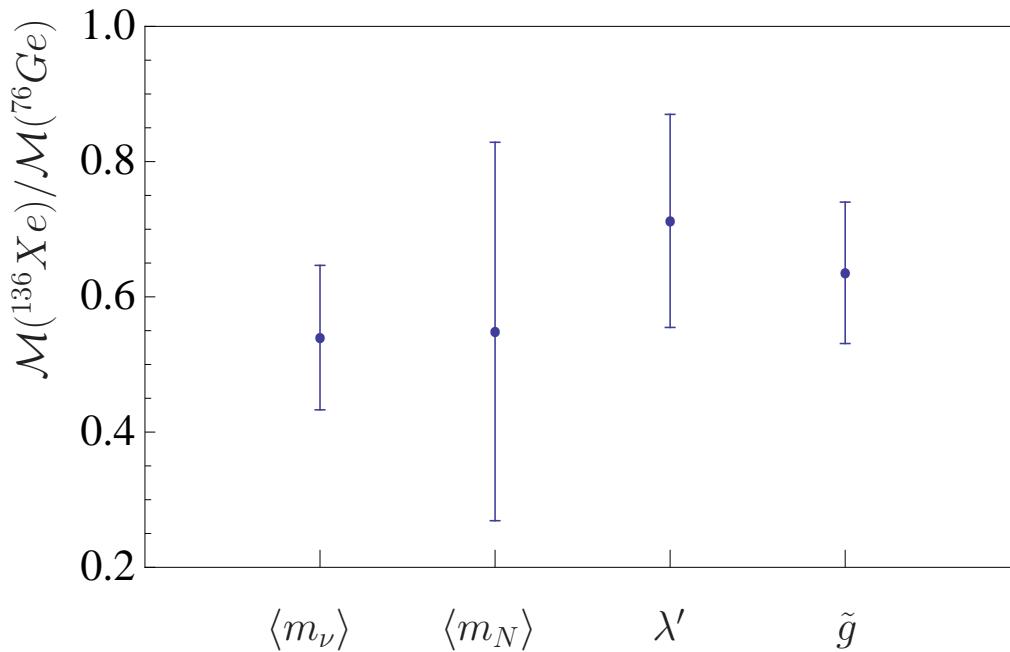
$\langle m_N \rangle$ - heavy neutrino exchange

λ' - “trilinear RPV”

\tilde{g} - gluino RPV



Ratios of matrix elements



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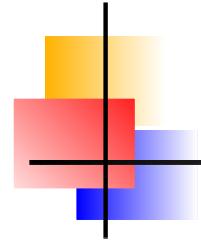
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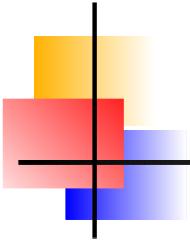
$\langle m_N \rangle$ - heavy neutrino exchange

λ' - “trilinear RPV”

\tilde{g} - gluino RPV



More on distinguishing mechanisms



Angular correlation

Calculate differential width:

$$\frac{d\Gamma}{d \cos \theta} \sim (1 - K \cos \theta)$$

For LR-models:

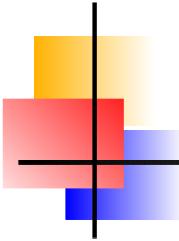
Doi, Kotani & Takasugi, 1985

For general LI Lagrangian:
Ali, Borisov & Zhuridov, 2007

⇒ Advantage: K depends strongly on mechanism, but weakly on nuclear matrix elements (i.e. weakly on isotope)

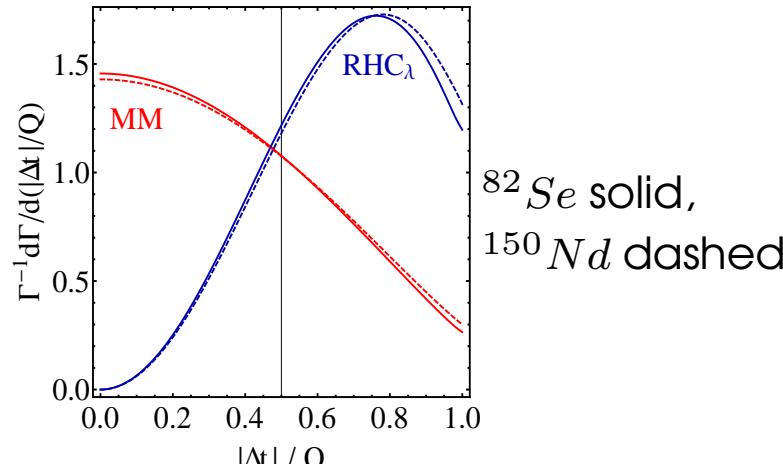
⇒ Disadvantage: Many terms in general Lagrangian lead to same (or very similar) angular dependence

⇒ Disadvantage: Most experiments calorimetric measurements only, exception: NEMO-III



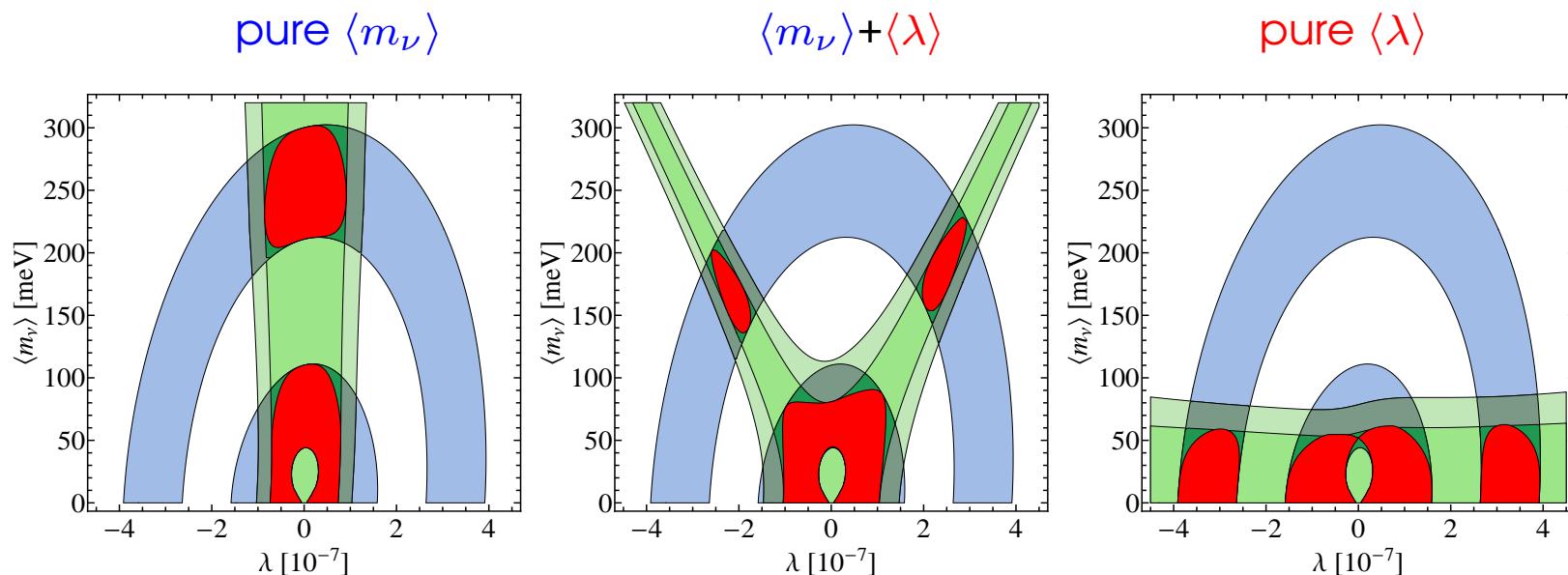
Super Nemo analysis

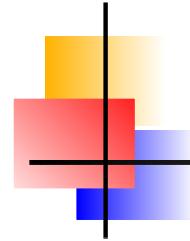
Arnold et. al, 2010



Below:

Outer contours:
 $T_{1/2}(^{82}\text{Se}) = 10^{25} \text{ yr}$
 Inner contours:
 $T_{1/2}(^{82}\text{Se}) = 10^{26} \text{ yr}$





Double beta plus decays

In $\beta^+\beta^+$ three principle decay modes:

$$0\nu\beta^+\beta^+: \quad (Z, N) \Rightarrow (Z - 2, N) + 2e^+$$

$$0\nu\beta^+/EC: \quad (Z, N) + e^- \Rightarrow (Z - 2, N) + e^+$$

$$0\nu EC/EC: \quad (Z, N) + 2e^- \Rightarrow (Z - 2, N)^*$$

For LR-models:

Hirsch et al., Z. Phys. A 1994

For general LI Lagrangian:

no publication exists

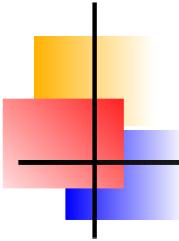
Numerical example: ^{124}Xe using pn-QRPA

Mode:	C_{mm}	$C_{\lambda\lambda}$	$C_{\lambda\lambda}/C_{mm}$
$0\nu\beta^+\beta^+$	$8.7 \cdot 10^{-17}$	$8.5 \cdot 10^{-18}$	0.098
$0\nu\beta^+/EC$	$1.6 \cdot 10^{-15}$	$2.2 \cdot 10^{-14}$	13.75

⇒ Advantage: Ratios (nearly) independent from nuclear matrix elements uncertainty

⇒ Disadvantage: Only $\langle \lambda \rangle$ enhanced

⇒ Disadvantage: Even best isotopes (at least) one order of magnitude slower than best $\beta^-\beta^-$



Others?

⇒ Compare rates ground state to 2^+

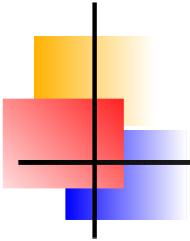
- Doi, Kotani & Takasugi, 1985: YES
- Tomoda, PLB 2000: NO for $\langle \eta \rangle$, maybe for $\langle \lambda \rangle$
- Disadvantage: several o.m. slower than g.s. transitions

⇒ Compare rates ground state to 0_1^+

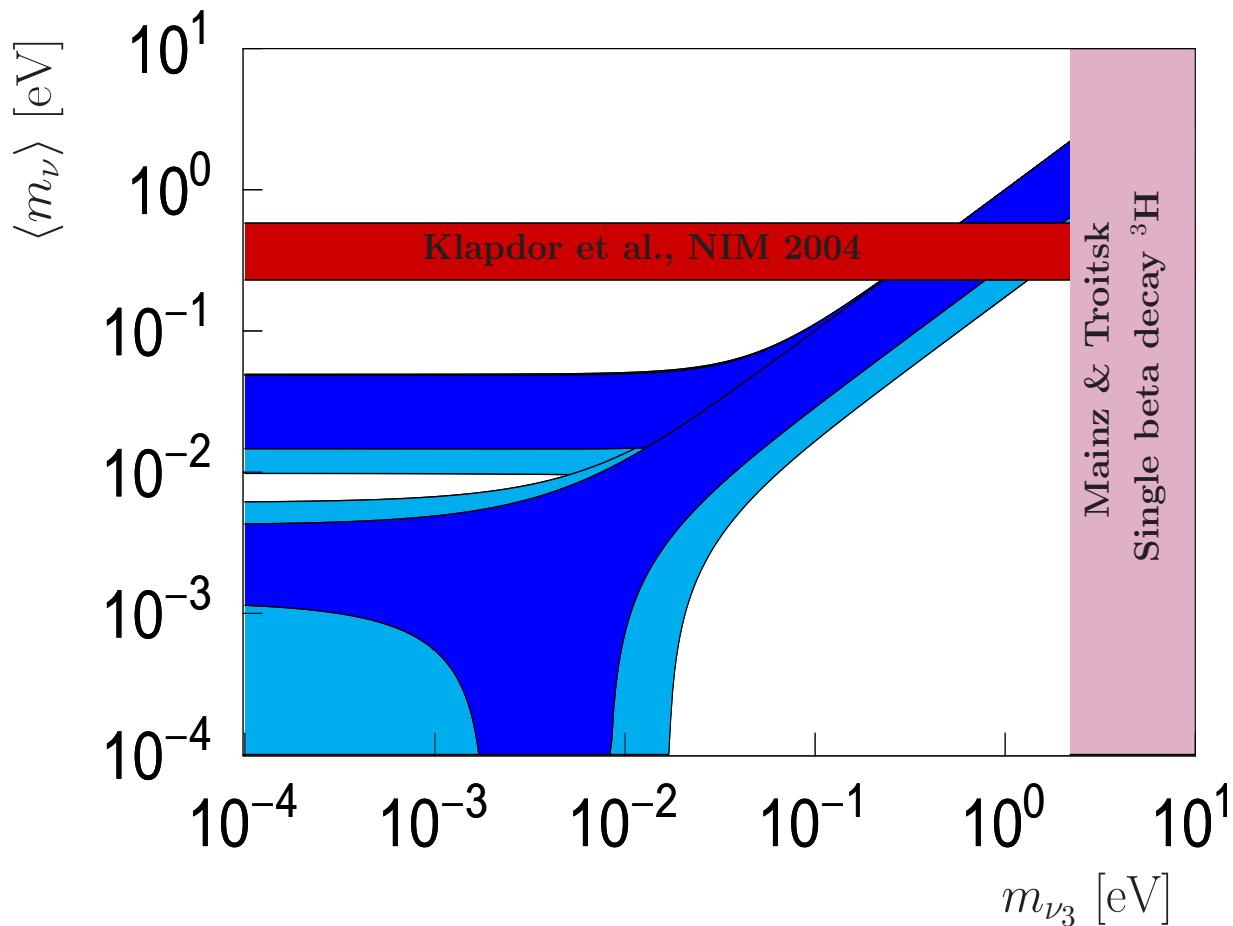
- Simkovic & Fäßler, Prog. Part. Nucl. Phys, 2002
- Disadvantage: (a) (about) 2 o.m. slower than g.s. transitions
- Disadvantage: (b) need to know matrix elements: $\Delta M \ll 40\%$

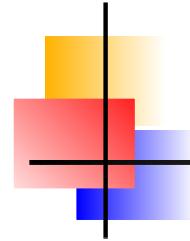
⇒ Compare rates, different nuclei

- Päs & Deppisch, PRL 2007; Gehman & Elliott, J. Phys. G 2007
- Disadvantage: need to know matrix elements: $\Delta M \ll x$,
 x differs for different particle physics, but is
strongly on model and on number of isotopes
- Faessler et al. PRD83, 113015:
not possible with realistic errors in NME

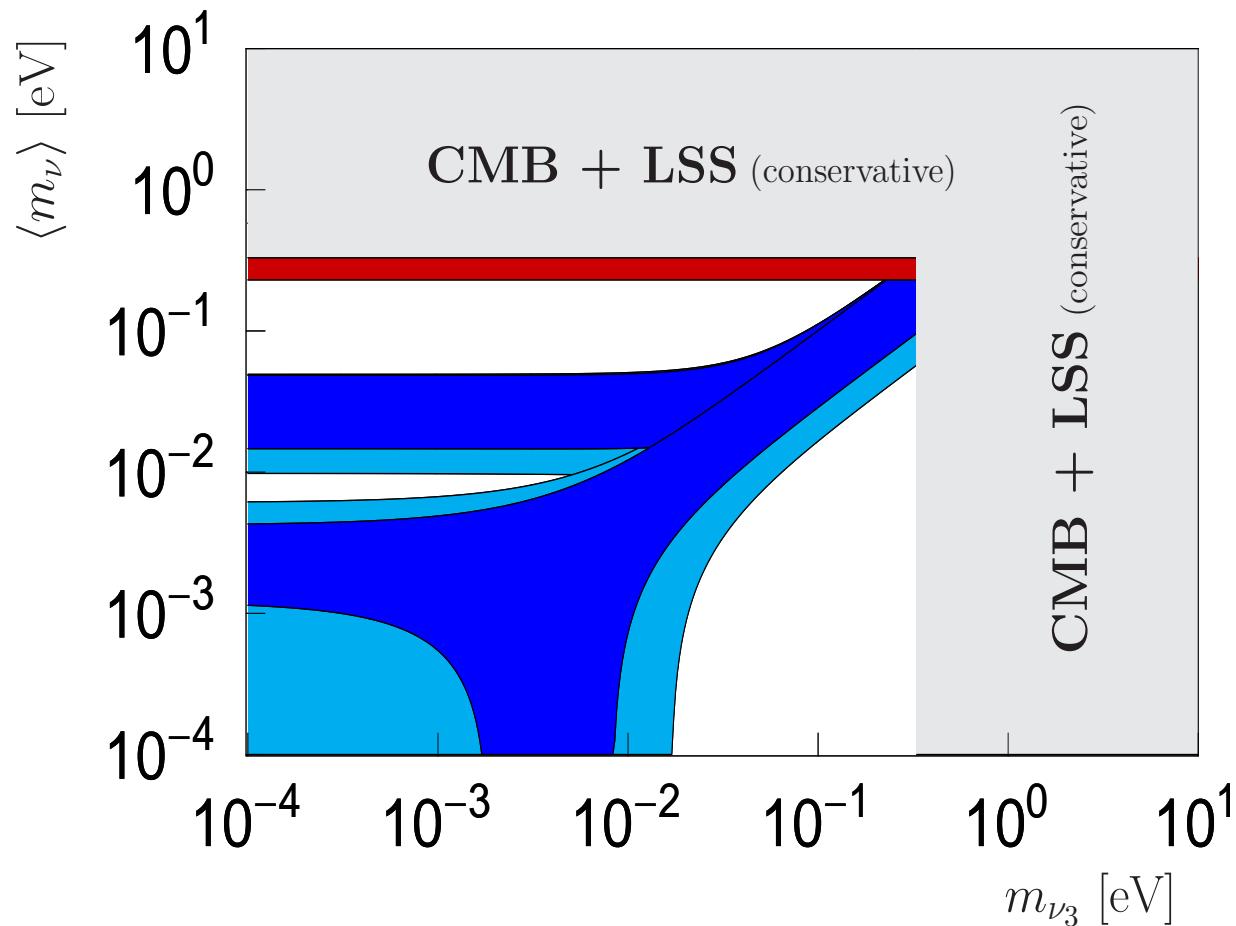


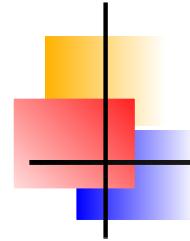
$\langle m_\nu \rangle$, single β & cosmology



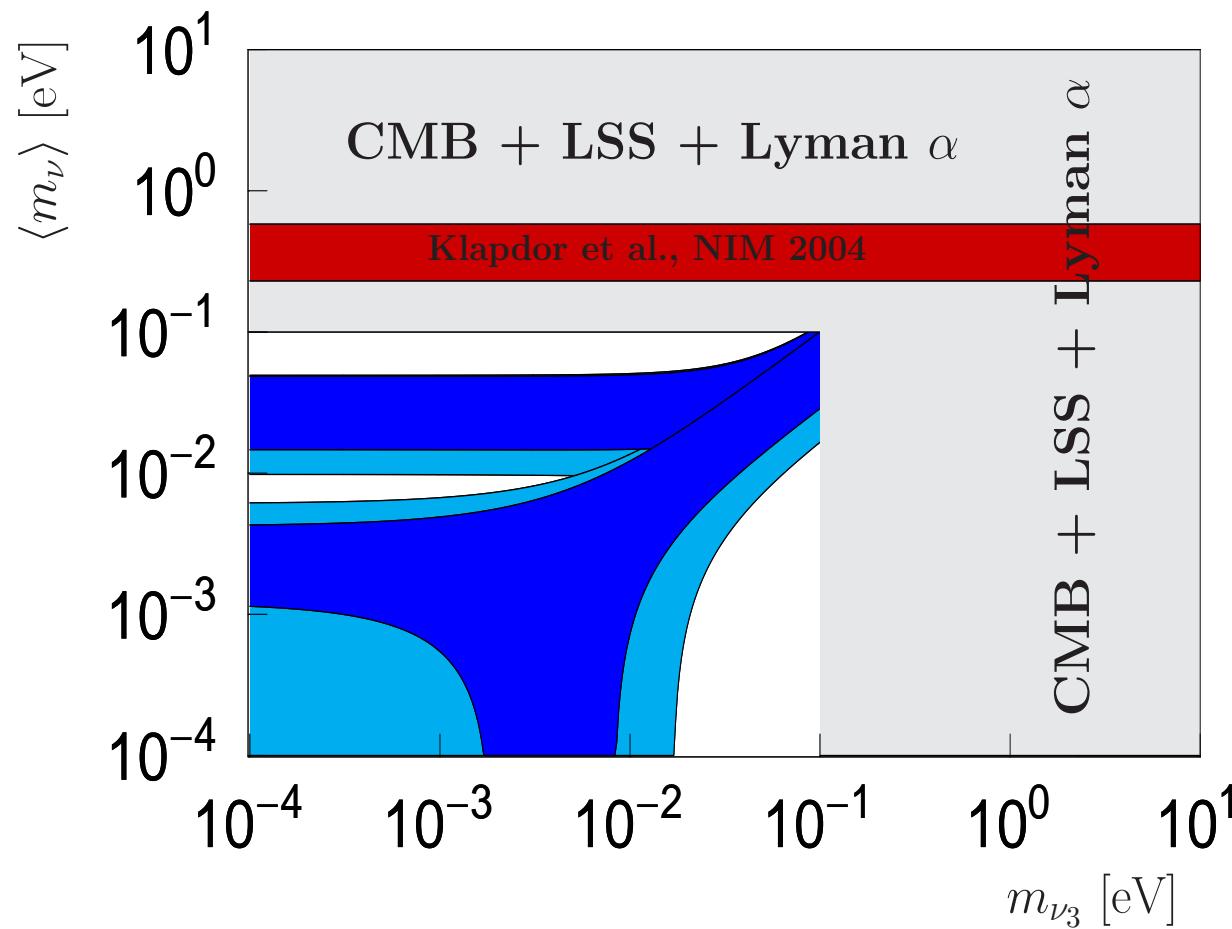


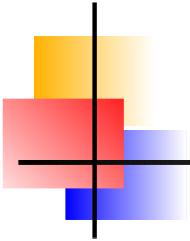
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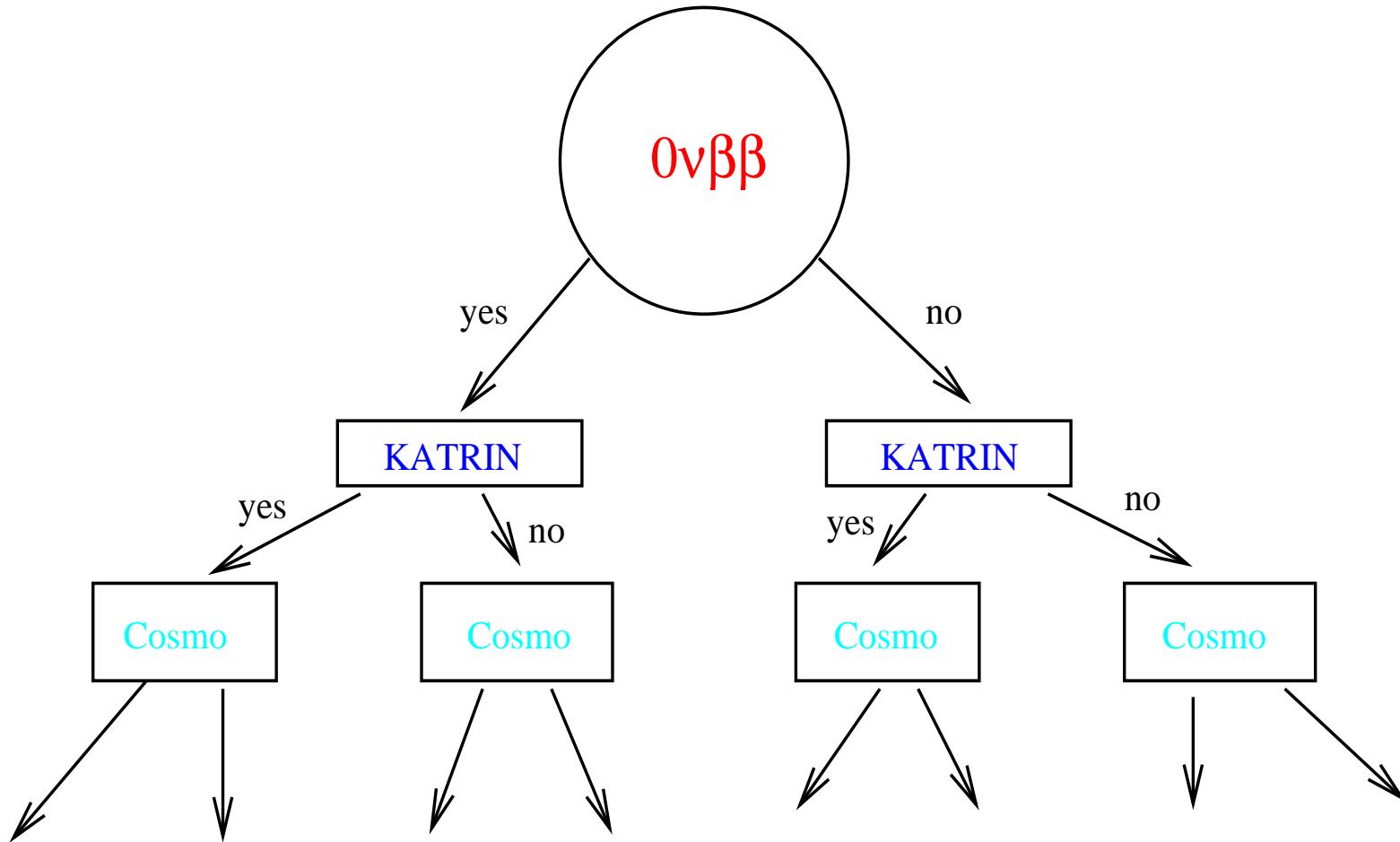


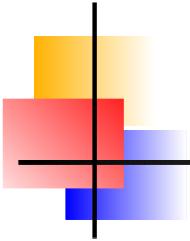


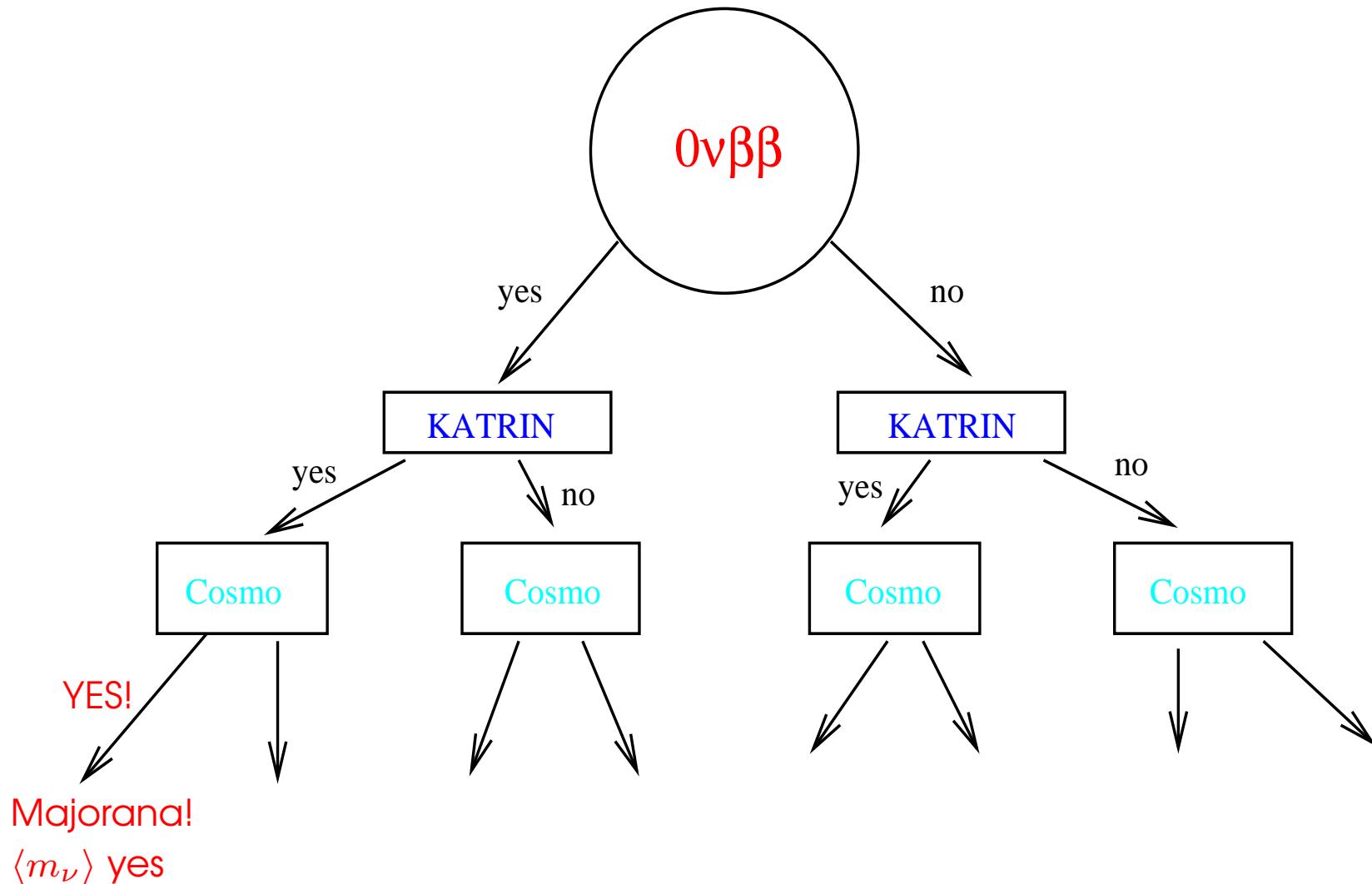
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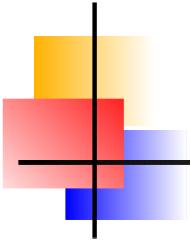


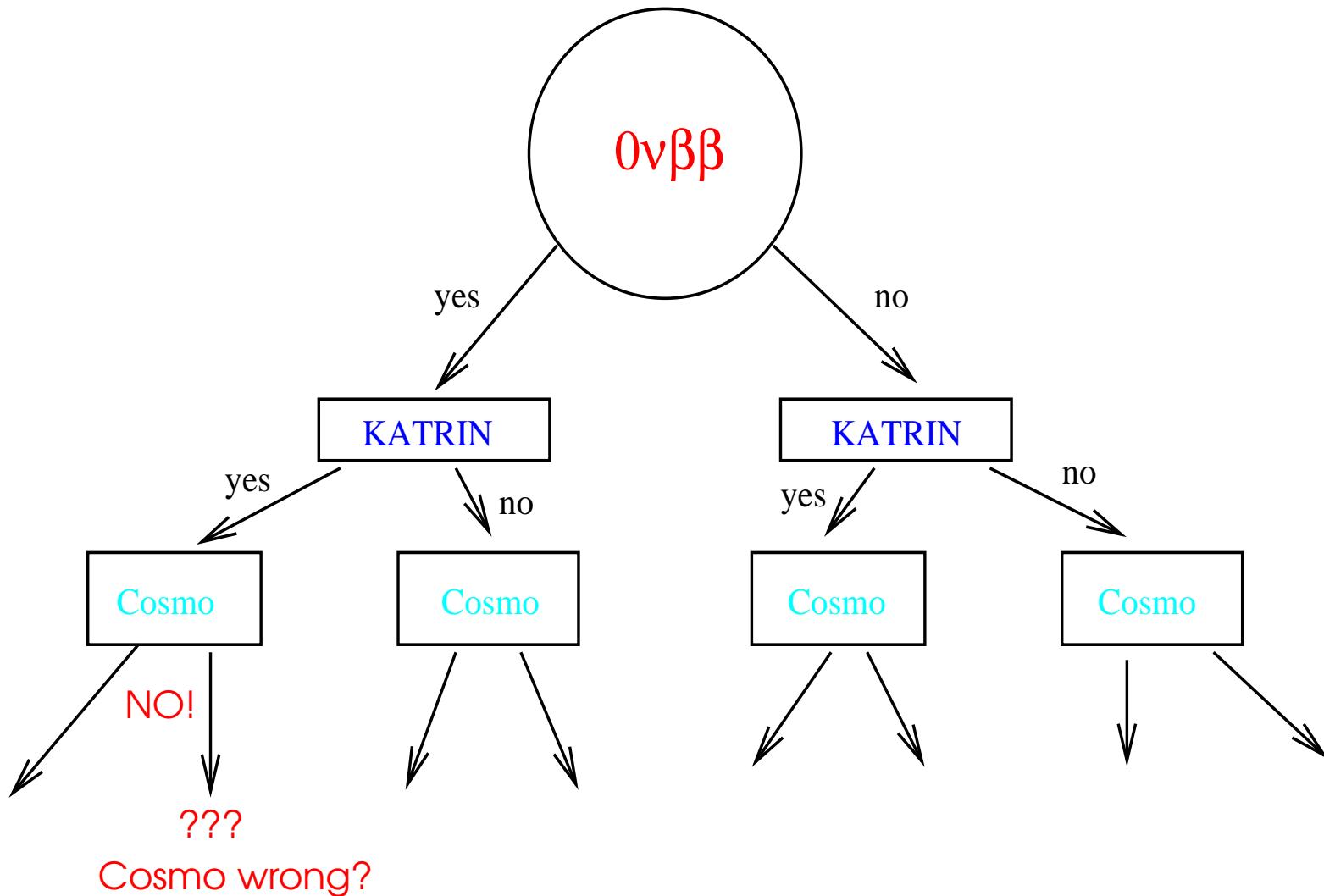

$$\langle m_\nu \rangle \gtrsim 200 \text{ meV}$$

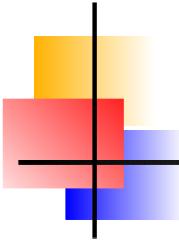


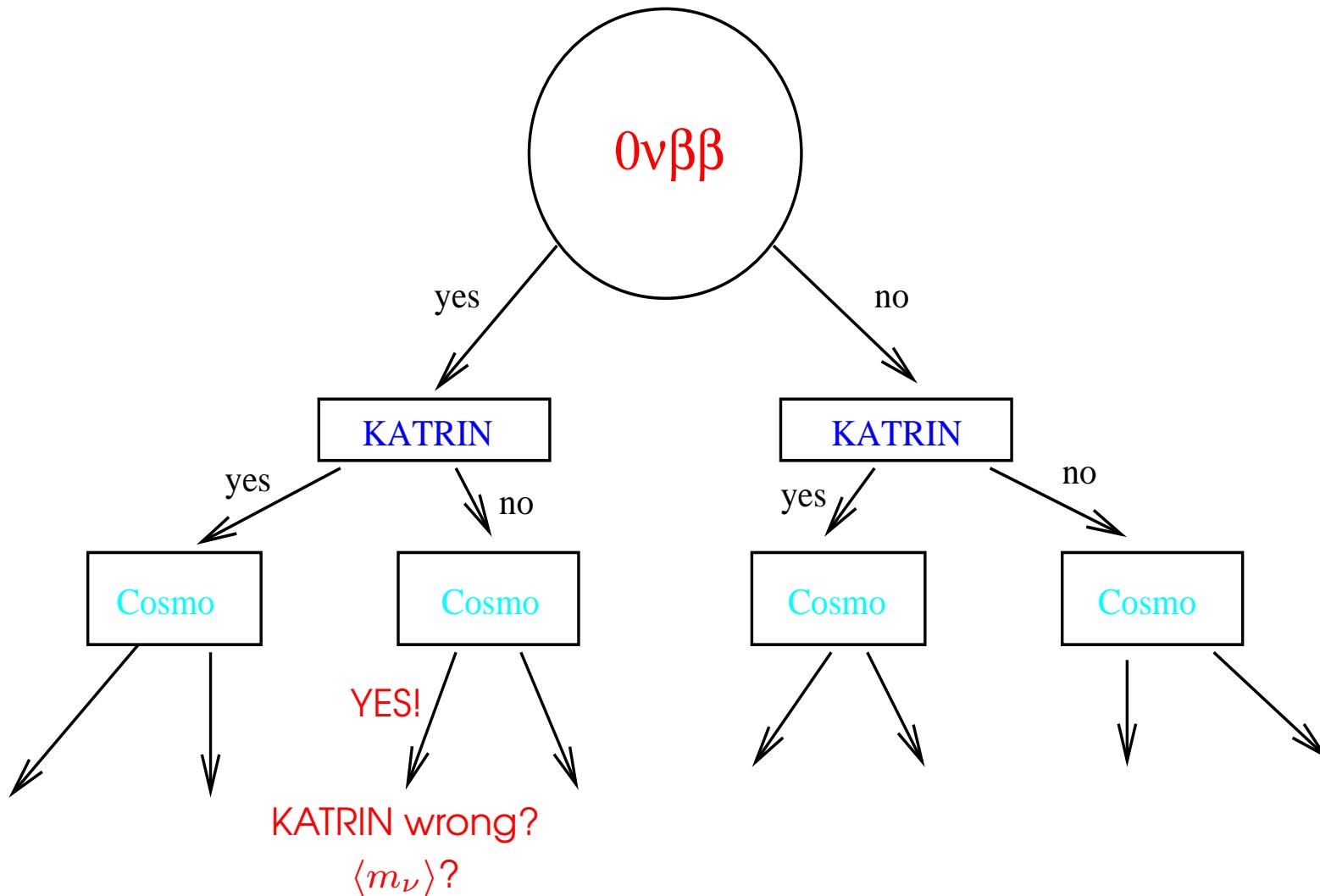

$$\langle m_\nu \rangle \gtrsim 200 \text{ meV}$$

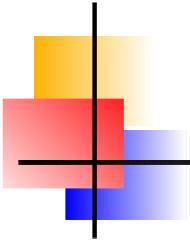



$$\langle m_\nu \rangle \gtrsim 200 \text{ meV}$$

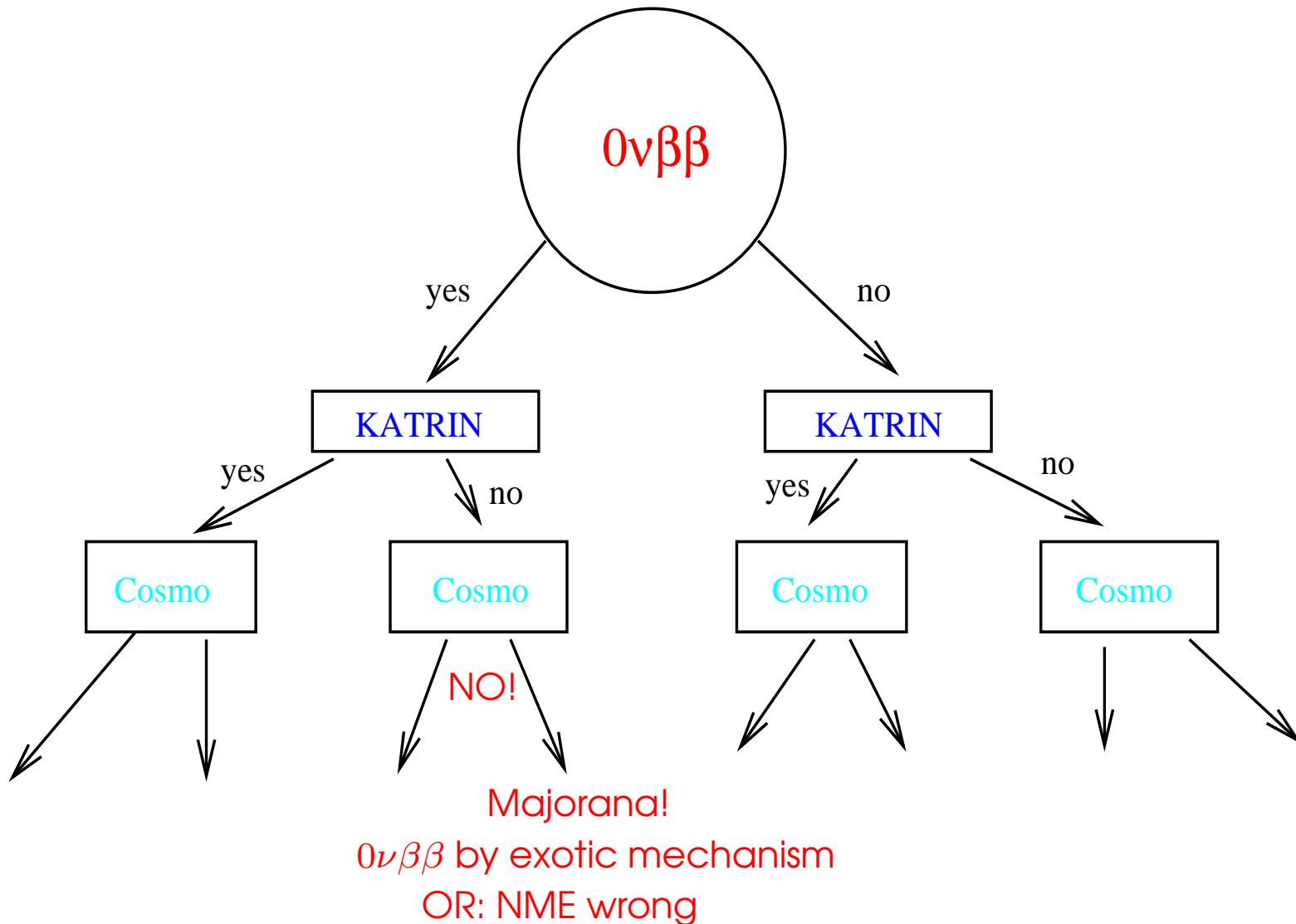


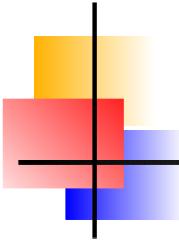

$$\langle m_\nu \rangle \gtrsim 200 \text{ meV}$$



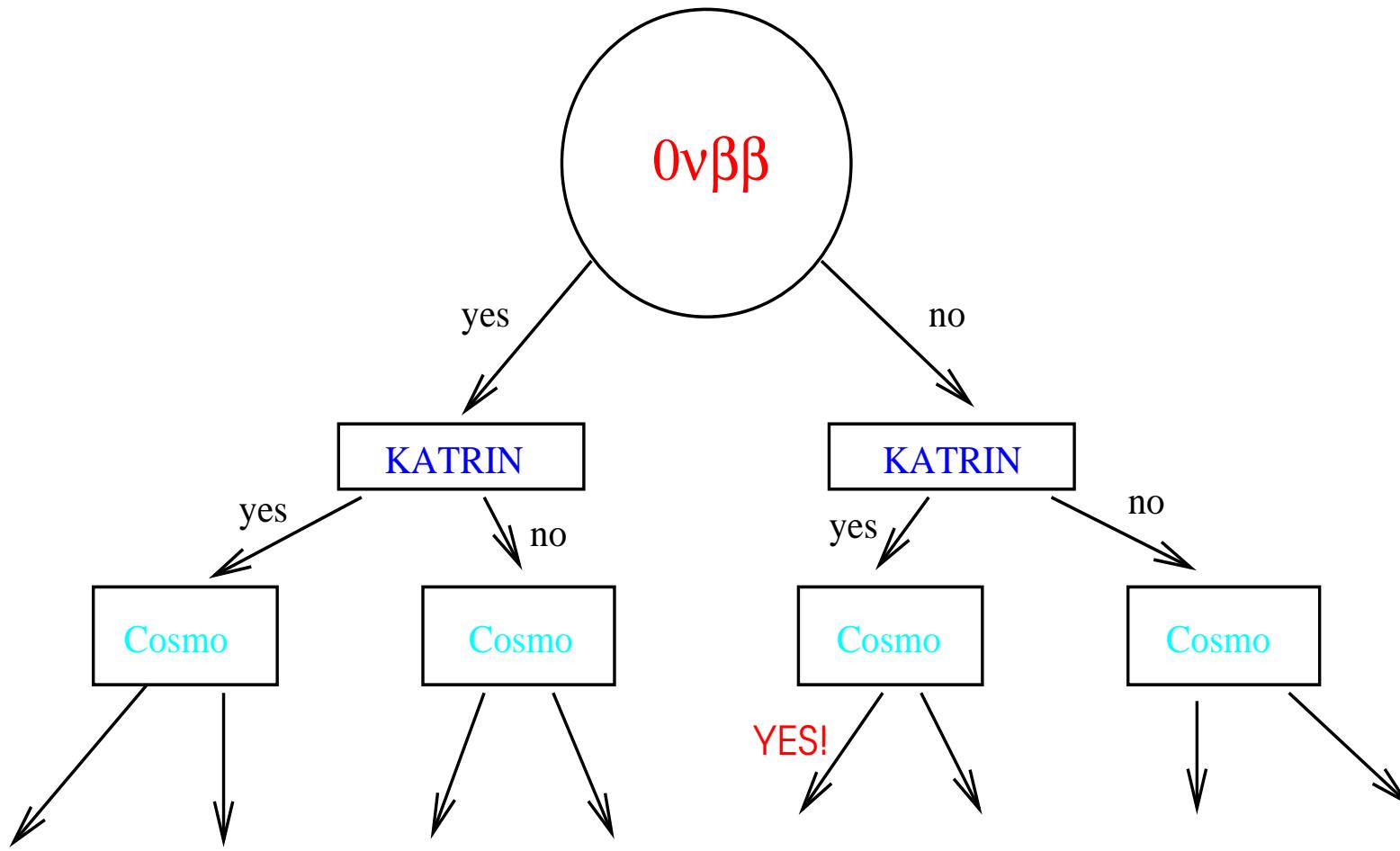


$$\langle m_\nu \rangle \gtrsim 200 \text{ meV}$$

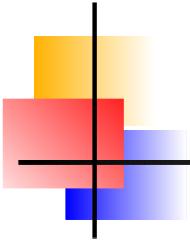


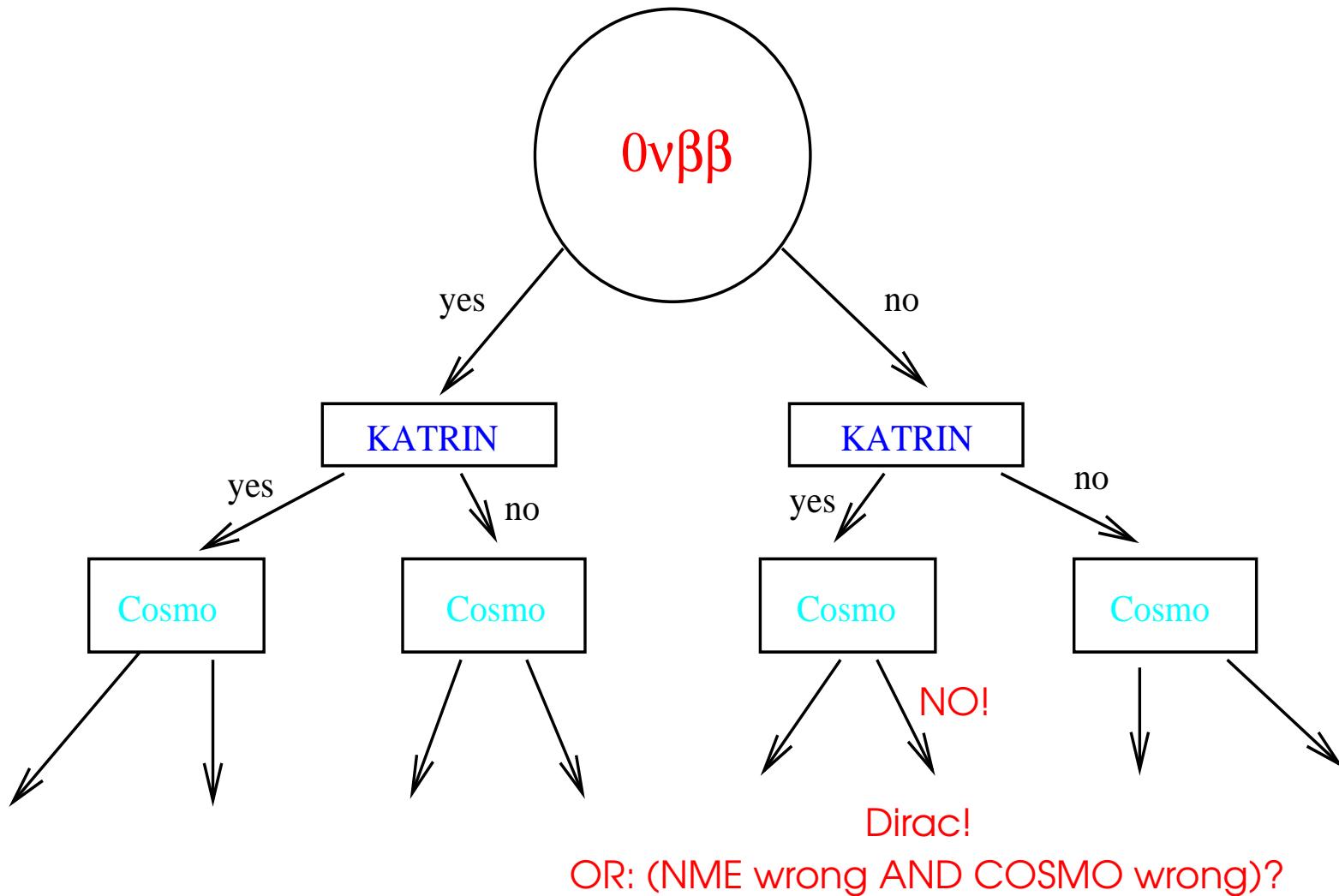


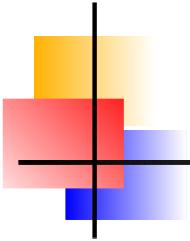
$$\langle m_\nu \rangle \gtrsim 200 \text{ meV}$$

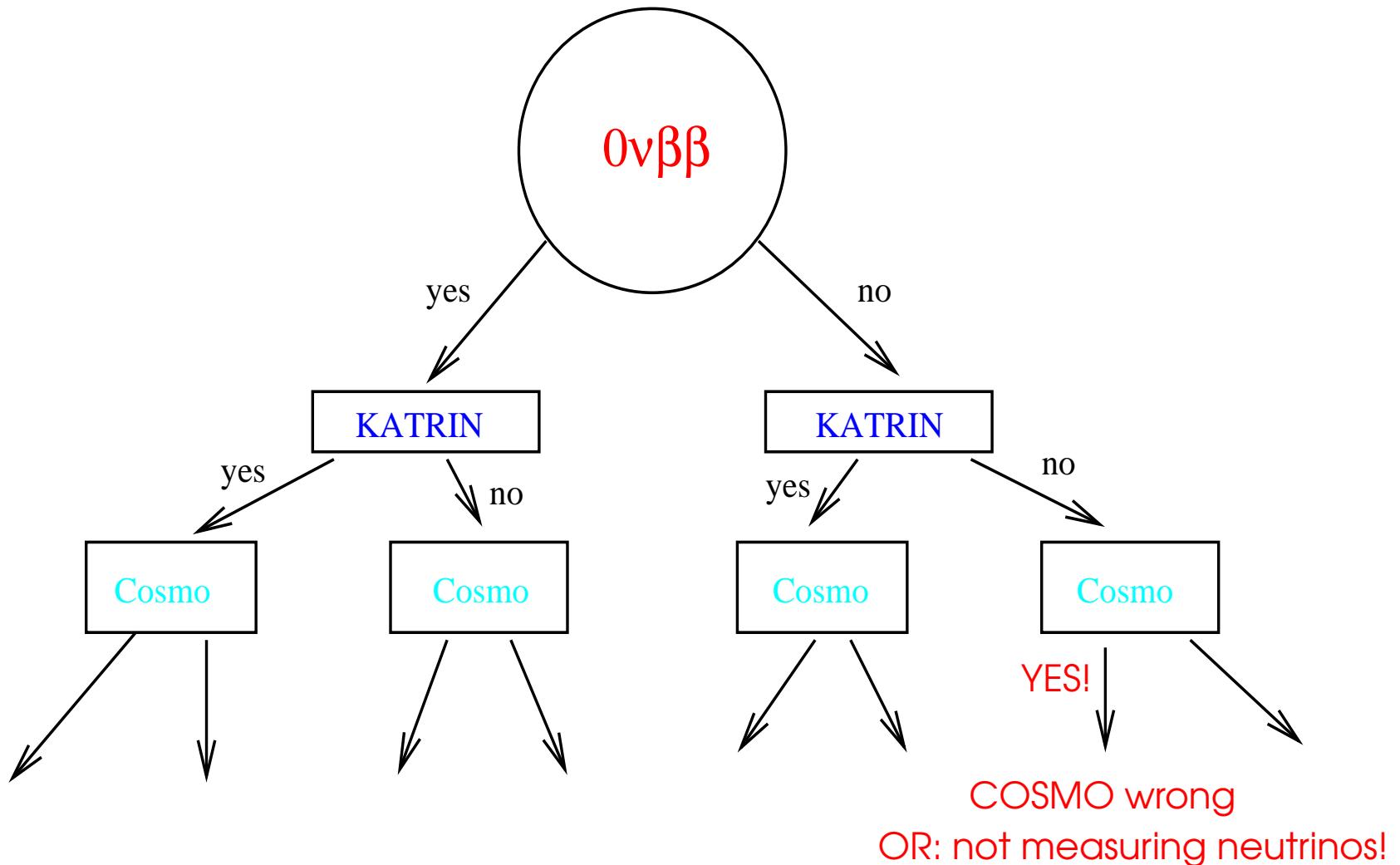


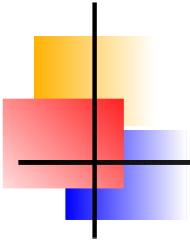
... or cancellation between $\langle m_\nu \rangle$ and exotic suppresses $0\nu\beta\beta$
OR: NME wrong

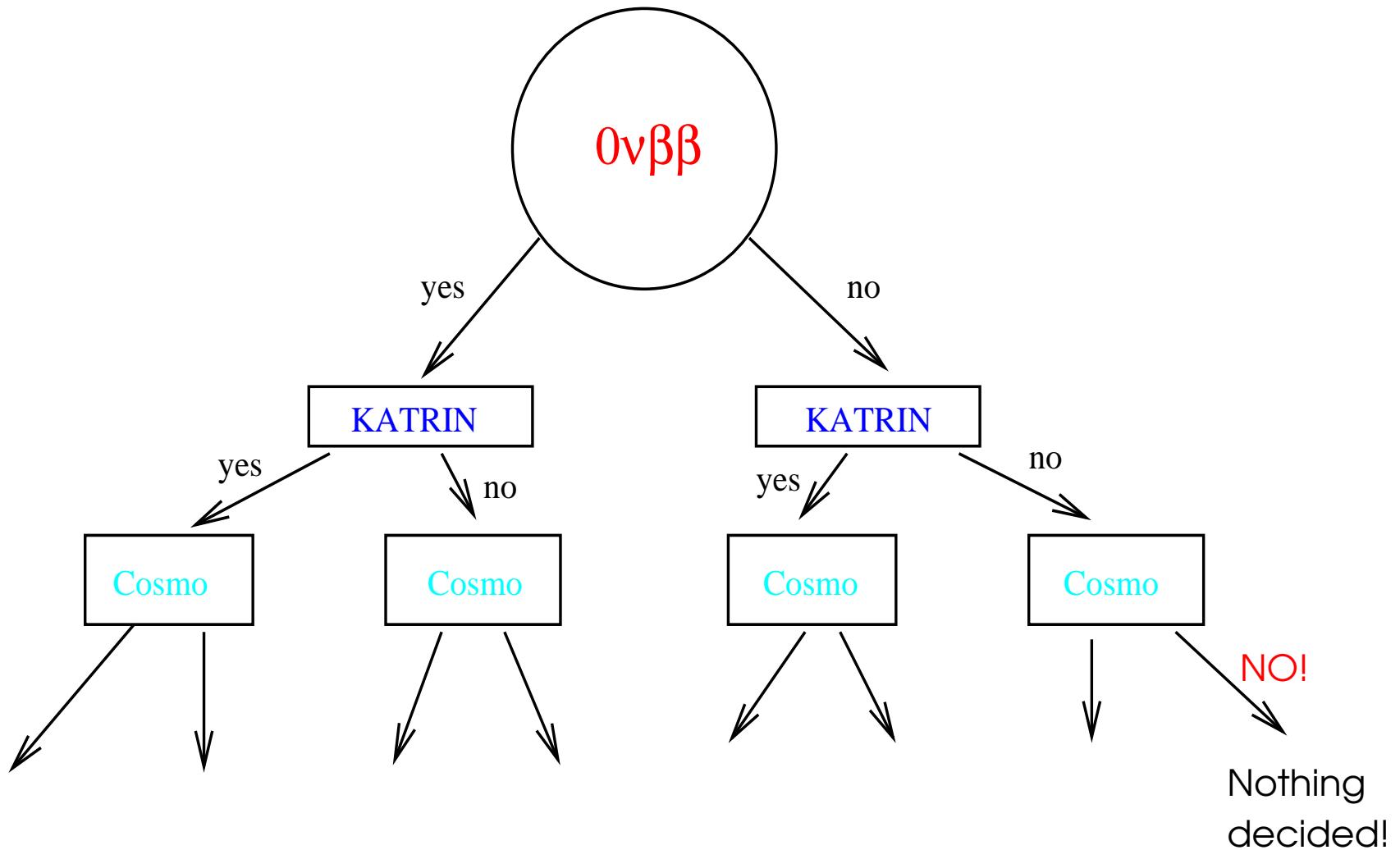

$$\langle m_\nu \rangle \gtrsim 200 \text{ meV}$$

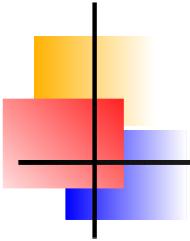


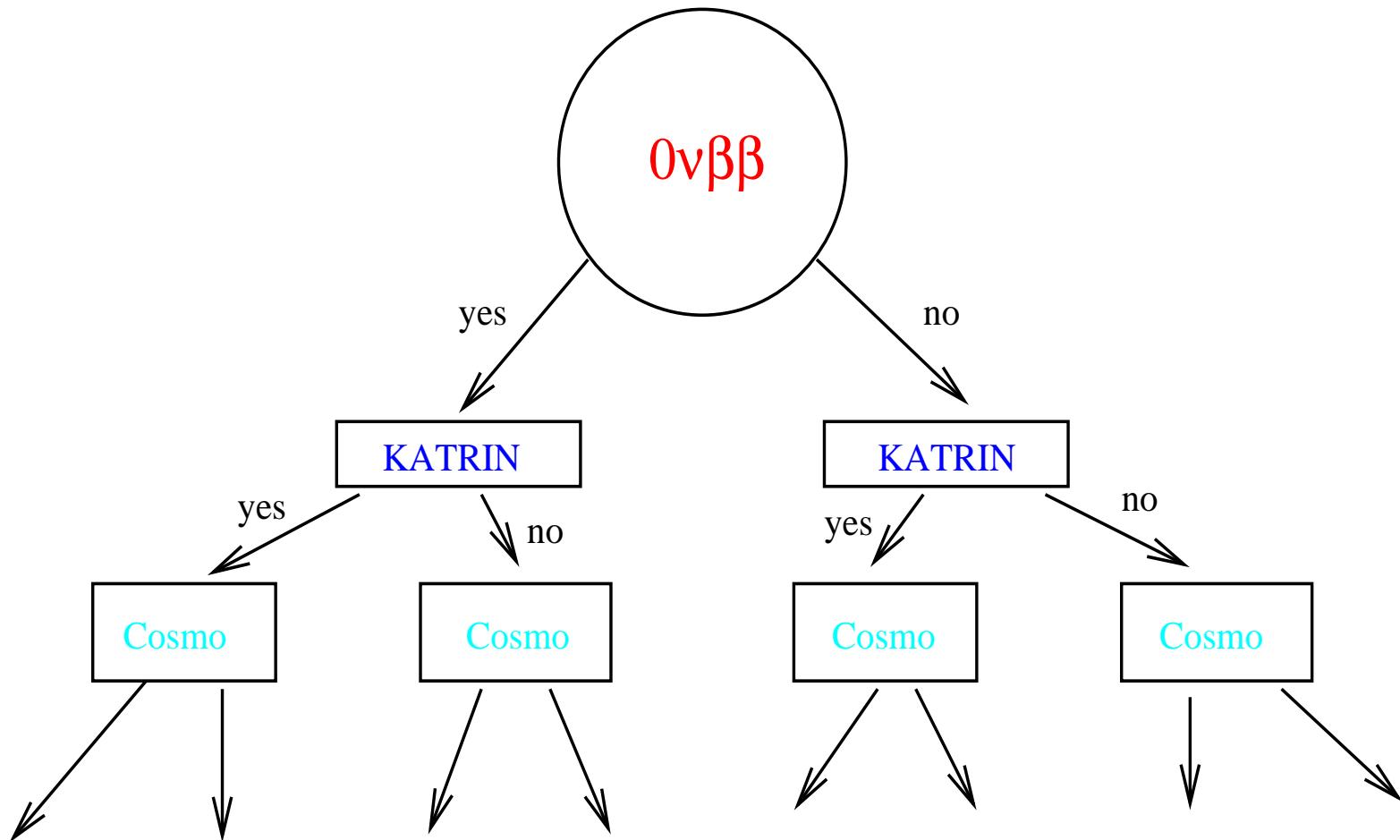

$$\langle m_\nu \rangle \gtrsim 200 \text{ meV}$$

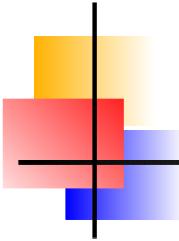


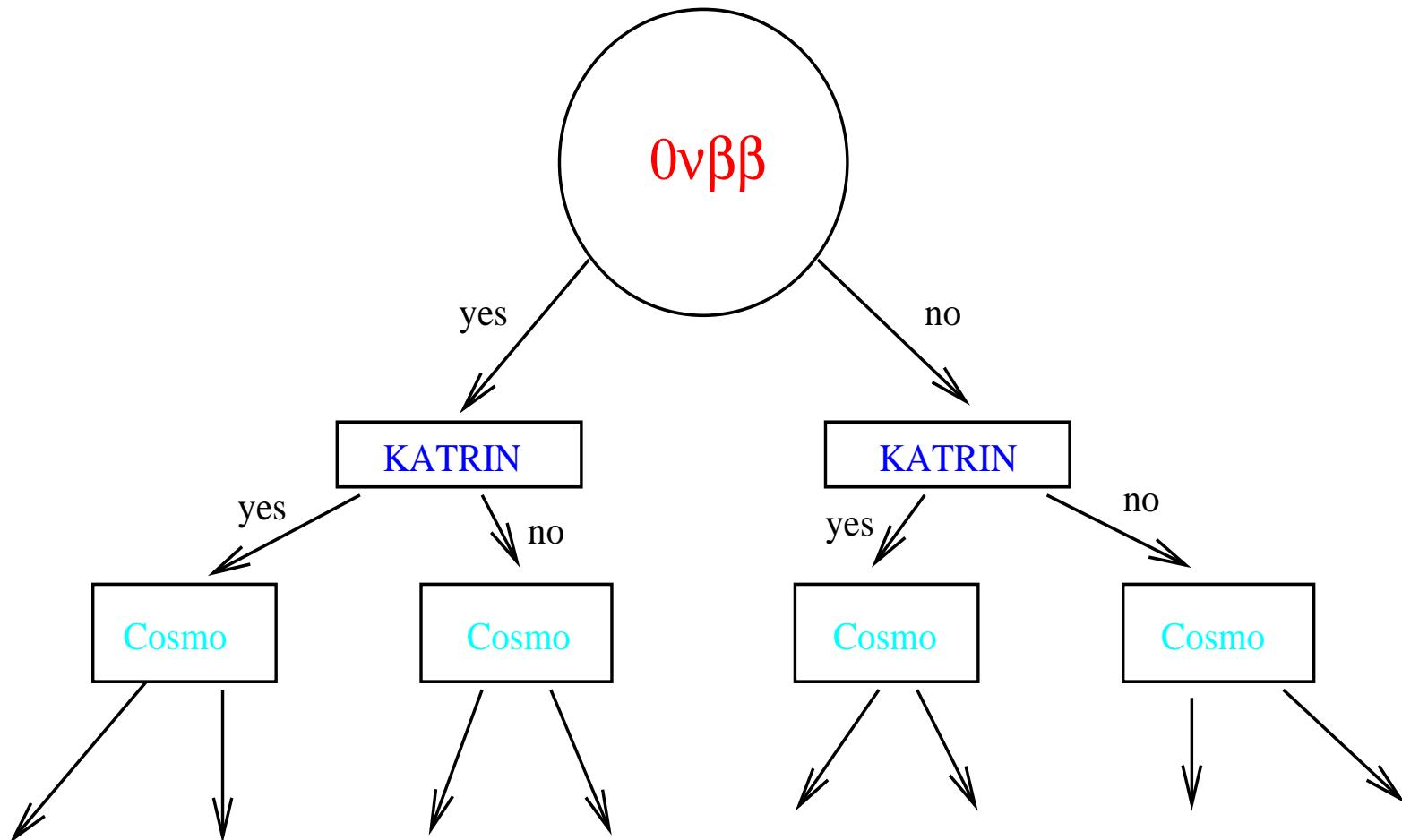

$$\langle m_\nu \rangle \gtrsim 200 \text{ meV}$$




$$\langle m_\nu \rangle \sim 20\text{-}50 \text{ meV}$$




$$\langle m_\nu \rangle \sim 20\text{-}50 \text{ meV}$$



Left as an exercise to the reader!